FACING UP TO NUCLEAR POWER

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PLAN FOR AN ECUMENICAL HEARING ON THE RISKS AND POTENTIALITIES OF THE FURTHER EXPANSION OF NUCLEAR POWER PROGRAMMES

I. ORIGIN AND PURPOSE OF THE HEARING

INTRODUCTION

The Central Committee of the World Council of Churches, meeting in Berlin, August 11-18, 1974, requested the officers and staff of Church and Society, to make a preliminary assessment of "the risks and potentialities of the expansion of nuclear power". The action of the Central Committee was in response to a recommendation of the W.C.C. Conference on Science and Technology for Human Development (Bucharest, June 24 – July 2, 1974), urging that "the WCC should initiate a study of the major moral, economic, social and scientific implications of the extension of atomic energy plants in the world".

In accordance with this request the sub-unit on Church and Society has begun consultations with nuclear scientists, political leaders and social planners seeking advice on the issues ot be considered.

The following proposals have been developed on the basis of these preliminary discussions.

THE URGENCY OF THE ISSUE

A number of factors have converged to increase the urgency of broader public examination of the consequences of the expansion of nuclear power. The oil embargo of 1973, the energy crisis linked with the rapid rise in the price of oil, and the possible exhaustion of fossil fuels have obliged many nations to press the search for alternative sources of energy, leading governments to move towards a more rapid development of nuclear power programmes than envisaged earlier.

Present estimates by the IAEA (International Atomic Energy Agency) and other bodies speak of accelerated increases of nuclear power production by 1985, and beyond that by the turn of the century. This would mean a large increase in the number of nuclear energy plants by 1985, a prospect which has aroused the concern of many scientists and lay persons alike.

As Dr Sigvard Eklund, Director General of the IAEA noted in his statement to the 18th Regular Session of the General Conference of the Agency (October 16, 1974): "In some countries there is, to put it mildly, a deep reluctance to accept nuclear power as a way out of the present difficulties."

The economic and social implications of these developments have also been alluded to in the Bucharest Conference Report:

> "A realistic appraisal of the implications of the nuclear process would seem to indicate unprecedented demands on capital, mineral resources and industrial capability, increasingly centralized systems of production, and a potentially large-scale environmental impact. The nuclear option entails a risk whose magnitude is a matter of debate. Widely divergent views of this risk are held in the scientific community. Many people find the risks unacceptable...". *Anticipation,* no. 19, November 1974, page 9).

THE CONTRIBUTION OF THE CHURCHES

It is obvious from what we have learned during our preliminary contacts and conversations that a proper evaluation of the factors which will influence public acceptability of expanded nuclear power cannot be easily or quickly accomplished. Moreover a number of organizations, including the IAEA and other U.N. agencies are already deploying considerable efforts to assess the risk and provide the proper safeguards. However we are left with the impression that the ethical values and social guidelines implicit in the present debate need to be clarified and that the churches might have a constructive contribution to make at this point. Church members, like almost everyone else, are only beginning to understand the enormous implications of the future of nuclear power development on a world-wide basis. An assessment by the World Council of Churches could help to encourage substantial discussion in the churches prior to the Nairobi Assembly and might also contribute to the discussion of the nuclear policy for the future which, at the international level, will be the concern of the next major IAEA Conference on Nuclear Power and its Fuel Cycle, in 1977, which will explore nuclear reactor strategy and the public acceptability issue.

II. FIVE DIVERGENT VIEWS

Such a preliminary assessment by the churches will not involve a major research study but an evaluation and synthesis of the divergent views that can now be identified in many countries. A brief description of essential elements of five positions emerging from the present debate is given here. It is not suggested that there are simply five distinct positions; in short form, this is supposed to be a sketch map that gives some indication of the many shades of grey rather than a black-and-white distinction "for" or "against". Note that it has been necessary to condense some of the major arguments.

A. WHOLLY NEGATIVE

At this extreme position at one end of the spectrum of opposing views, it is possible to group together a number of ethical, political, economic and technical concerns. These can be described as follows:

1. **Social/Ethical Dimension**
It can be argued that future generations will inherit the problems of nuclear power development, particularly those relating to the safe management of obsolete reactor systems or the prolonged storage of high specific activity radioactive wastes. To the extent that unborn children will have to bear a significant fraction of the costs of energy production for the present era, there is moral obligation on the operators to secure all loopholes in the process of designing and engineering these systems. This aspect must not be underplayed for economic reasons.

2. **Political Concerns**
In many countries, nuclear development programmes will remain under direct Government control, with the result that the planning of large nuclear programmes may not be subject to independent appraisal or any degree of outside comment. The defence status of some of these installations will inevitably bring down a security blanked once the reactors are operational. The institutionalized separation of these plants may be necessary even in democratic states, but this does not necessarily lead to confidence in the overall political control of the technology.

3. **Nuclear Safeguards at an International Level**
There is a body of opinion which believes that the present scale of international machinery for administering nuclear safeguards and monitoring national programmes is already inadequate in the light of prospective sales of nuclear power reactors. The need for some immediate improvement in the situation through regional centres of control rather than a single centralized authority is now apparent.

4. **Economics of Nuclear Power Generation**
A new school of energy analysis has advanced the view that while the economic viability of nuclear power in competition with other systems of electricity generation is now proven, the overall energy costs in a rapidly expanding nuclear programme can offset some of the obvious advantages. This can best be illustrated in the following diagrams (Chapman, 1974):

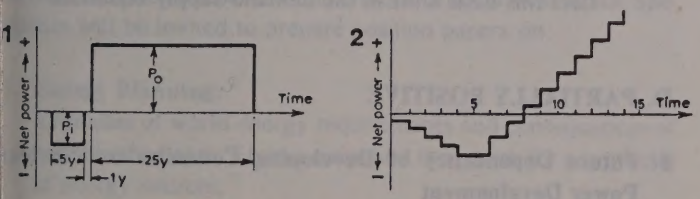

Figure 1: Energy consumption during building then energy production afterwards for a nuclear reactor with an energy ratio (E_R) of 10.

Figure 2: Variation in net power when a reactor of $E_R = 10$ is ordered each year.

According to this approach, a linear increase in the growth of nuclear power (one reactor ordered per year) indicates that it takes 13 years to produce a net energy output. There is an equally valid argument which suggests that the decommissioning costs of large nuclear installations might, at present rates of inflation, correspond to as much as 80% of the initial capital costs of construction.

5. **Economic Self-Reliance must be based on Equilibrium Sources of Energy**
In the developing world, it is very debatable whether the introduction of nuclear power can be defended in terms other than the pragmatic response of politicians threatened by an increasing balance-of-payments problem on the oil imports account. The smaller decentralized systems of power generation based on solar energy, wind, geothermal and hydroelectric power are more compatible with the manpower training programmes in most of these countries and should not be dismissed since they represent the best long-term prospect of energy self-sufficiency at the community level. This viewpoint is in line with the "technological opposition" who contend that alternative sources of energy will be developed, thereby replacing the need for widely proliferating nuclear power programmes.

B. PARTIALLY NEGATIVE

This is a discriminatory view based upon the merits of different fuel cycles, and consequently it reflects a more detailed knowledge of the design variables ranging from the current evaluation of thermal reactor types to the more advanced fast breeder concepts.

1. **Detailed Cost Analysis**
It is accepted that long-term factors, such as the costs of waste management (10 half lives of $^{239}Pu = 10 \times 24{,}000$ yrs.), should be properly reflected in the total costs of fuel recycling. New technological solutions to this kind of problem should also be examined in terms of the energy cost element and included in the overall energy balance of the particular nuclear power system.

2. **Environmental Impact**
The assessment of the impact of large energy projects on the natural environment is a comparatively recent requirement inside the planning legislation of even the industrialized countries. In a strictly operational sense (day-to-day), large nuclear power stations may compare quite favourably with conventional power stations utilizing fossil fuels, because of absence of large direct emissions of combustion products. Thermal pollution is acknowledged to be a considerable restraint on the siting of all types of centralized power stations. Under accident conditions (such as a loss-of-coolant accident), nuclear power systems introduce an additional dimension of risk that should be more openly assessed and generally understood by the public at large. While there may be specialist design solutions, the operational reliability of such systems must also be validated.

3. **Security Risk**
Responsibility for the security of nuclear operations resides with the licensing authority in each country. Under normal circumstances, this arrangement will probably function adequately, but in the present world, the threat of external terrorist activities cannot be lightly discounted. Since it is the transport of nuclear fuel materials between reactors and fuel reprocessing facilities that represent the most vulnerable linkages in the chain of operations, special security arrangements alone may not be sufficient to contain the risk of diversion. A total review of the nuclear handling systems in each country is now a matter of first priority.

4. Enlarged Plutonium Hazard for Breeder Reactors

Many technical experts in the nuclear power field have substantial reservations concerning the widespread development of fast breeder reactors incorporating a plutonium fuel cycle. In several countries, prototype fast reactors are already operational, so that with increasing pressure on the world uranium market, it seems inevitable that the higher conversion factors available in a $^{238}U/^{239}Pu$ breeding cycle will prove to be economically attractive. Substantial plutonium inventories, far exceeding present levels, will result in a new order of radiological hazard. The large scale introduction of this technology may be imminent; it will certainly remain as one of the most controversial aspects of nuclear power development in the period beyond 1985.

5. Rate of Nuclear Power Development

With countries in the industrialized and in the developing world already subject to considerable restraints in capital expenditure resulting from the present disturbances in the world monetary system, it can be reliably argued that energy conservation has become a matter of immediate priority in most cases. It is not clear to what extent this movement will constrain the growth of nuclear power programmes in view of the long lead time for construction that are now an accepted part of the forecasting and planning dilemma.

C. MIDDLE VIEW

The balance point between the economic attractions of low cost nuclear power from a range of available systems and the seemingly inevitable risks of increasing dependency on this highly complex technology will be central to the debate on future energy supplies. The feasibility of nuclear power in all its forms has been a preoccupation of industrialized countries for the past 30 years. Massive investment and commitment at the national level will not be simply passed over in response to pressure group activities from outside the industry. It would be wrong in many cases to deny that nuclear power has a major contribution to make in providing electricity for large urban conurbations. It would be equally wrong to imply a total dependency on nuclear power as the ultimate source of energy for the future. The middle view should advance a reasoned perspective of the place of nuclear power in the overall energy balance.

1. Synthesis

Although there are many variables and unknowns in the energy equation, a first approximation to the most reasonable balance between all available energy sources, including nuclear power, should be introduced into the debate. This will provide a general guideline on the projected significance of nuclear power development in contrast to the alternative sources, including fossil fuels, solar and geothermal energy.

2. Risk-Benefit Criteria

The introduction of social and environmental factors governing nuclear power alongside the orthodox economic criteria, will bring the analysis closer to the domain of public understanding and acceptability. Multidisciplinary teams sponsored by international agencies are probably best equipped to advance a general analytical framework which can then be adapted to national and regional situations. International standards on the siting criteria, ancillary planning legislation and licensing procedures for nuclear plant should be subject to scrutiny by an independent jury with no formalized commitment to nuclear power systems.

3. Nuclear Plant Operations Secured

Increased levels of security at the level of individual nuclear power plants will be complemented by shared responsibilities for processing fuels at international regional facilities. This will be essential if nuclear power plants are introduced in large numbers to countries in Latin America, Africa and Asia. Without access to localized reprocessing facilities, the transport problems would be formidable with a concomitant increase in the risk of diversion or accidental dispersion. This is a planning problem of a unique kind; within the boundaries of human fallibility, the engineering component can no longer be based on trial-and-error principles.

4. Management Strategies

a. A slowdown in the introduction of "advanced" nuclear systems, e.g., the liquid metal fast breeder reactor, will allow the consolidation of present day engineering competence in the nuclear power field. This strategy is particularly important if countries are to be persuaded **not** to jump the technology "gap" into this more uncertain end of the nuclear power spectrum.

b. While each country will seek to achieve the optional fuel mix that is most immediately compatible with its prospects for economic development, this does not necessarily lead to a zero energy growth situation in every case. There is nevertheless a wide margin of wasteful energy use in most industrialized countries that can be eliminated; the time scale for achieving this is not likely to be less than 10-15 years.

c. Adaptation to new life styles requiring a different pattern of energy use will almost certainly become one of the principal challenges to people in all countries. In the process it should be possible to introduce the alternative systems of energy production that are more in line with individual or community needs in many countries, particularly in the developing world. It remains to be seen whether the constraints may warrant a form of energy rationing that reflect this basic shift in the demand-supply equation.

D. PARTIALLY POSITIVE

1. Future Dependency of Developing Countries on Nuclear Power Development

As a result of the upward movement of the price of crude oil in world markets, the smaller scale of nuclear power plant (100-400 MW(e)) is now economically competitive with the conventional forms of electrical generation. In countries where there is already a declared commitment to nuclear power, this probably means an increased dependency over that already planned for the next decade; countries such as India and Brazil would appear to be in that category. There is also the possibility that some countries with a surplus of revenues from the petroleum markets may now be preparing to enter the nuclear power field.

2. Standardized Approach to Nuclear Power Development

There is a good deal of engineering wisdom behind the view

that only a very standardized pattern of nuclear reactor types should be offered to countries on the threshold of a commitment to nuclear power. This would serve to minimize the uncertainty arising out of reactor performance in widely varying load-following situations. It would also enable the operators to become more familiar with safe-operating procedures and fuel handling requirements for a reactor series constructed over a fairly long period.

3. **Investment and Manpower Training**
It is obvious that both of these factors are highly interconnected. The capital demands for the successful implementation of a nuclear power programme are likely to be large and immediate. At the same time, it would be completely unworkable to embark upon the first phase of development without a suitable national catchment of scientific and engineering expertise in the major nuclear disciplines. This investment must equally reflect a capability for handling each stage in the fuel cycle at some reasonable date in the future, otherwise there is an implied dependency on the industrialized countries that are currently marketing the systems. In order to participate in the full economic benefits, investment in shared regional facilities for fuel reprocessing may be necessary between groups of countries at comparable stages of development.

E. WHOLLY POSITIVE

1. **Nuclear Salesmanship**
This is undoubtedly the province of the national nuclear corporation or the multi-national combine with an urgent need to recoup some of the massive research and development expenditures incurred in bringing a reactor concept to the market place. The prospect of an expanding market has failed to materialize time and time again during the past decade or so. While design safeguards and operational risks vary from one design to another, this is certainly not an area where aggressive salesmanship should be allowed a free interplay at the expense of the highest possible standards of international regulation and control.

2. **No Reliable Alternatives**
It will be strongly argued from this position that virtually all the alternative systems of energy production suggested for industrialized countries are far from proven in economic as well as in hard practical terms. To proceed without the benefits of widespread utilization of nuclear power would be considered both imprudent and totally unrealistic, given the scale of energy demand that the world is facing. Despite the finite element of risk, the place of nuclear power in most advanced economies is now guaranteed for that reason. The position is obviously not so clear cut in the developing world, but here again, nuclear power represents a hedge against uncertainty, if only because the viability of alternative energy sources has not been adequately demonstrated.

3. **The Future Potential**
If the standardized nuclear reactor package for developing countries is accepted as a workable concept, subject to the necessary implementation of international nuclear safeguards under the terms of the Non-Proliferation Treaty, then the world is embarked upon a broadly-based scenario for nuclear power development. There is a need to state that this path will conceivably lead on from thermal reactors to the fast breeder, from fission to fusion systems. Comparable hazards exist over the whole range of reactor types, but the trade-off could be the energy that humanity needs to survive in the quantities that reasonable men and women agree exists in theory.

III. ASSESSMENT OF DIVERGENT VIEWS

In assessing the merits of these views we deem it necessary to make a systematic review and critique of six critical topics. Specialists will be invited to prepare position papers on:

1. **Energy Planning:**
Estimates of world energy requirements and consequences of possible shortages. Energy ratios and the search for a synthesis of energy sources.
Economic Criteria: Evaluation of oil price movements and case for nuclear energy on economic and technological grounds; economic advantages of different energy systems.
(Presentation by an energy economist)

2. **Energy Options for Developing Countries:**
Presentation of African, Asian and Latin American energy needs.
(Presentations by one or two energy specialists from these countries)

3. **Risk Assessment:**
Public acceptability criteria – based on comparison with other risks of a transient kind. The introduction of "permanent" damage to the biosphere as a new order of risk.
(Presentation by a staff person from the Division of Nuclear Safety and Environmental Protection, International Atomic Energy Agency)

4. **Radiological Hazards:**
Background radiation associated with large-scale nuclear power programmes; maximum permissible levels of radiation to the public at large. The assumptions concerning the siting of nuclear power complexes, fuel processing plants and long-term storage facilities in terms of the localized hazards.
(Presentation by health physicist)

5. **Operational Hazards:**
Thermal pollution, waste management (especially the international aspects); the problems of maintaining a proper plutonium inventory with the increasing scale of nuclear power development. Standards for transportation of irradiated fuel elements. Plutonium diversion, the proliferation of nuclear materials, fuel reprocessing and the implementation of safeguards.
(Presentation by a French or American nuclear scientist)

6. **Ethical and Social Issues:**
   a. Theological and ethical implications of "hypotheticality" or the "Faustian Bargain" as an attribute of nuclear technology. The morality of risk taking.
   b. The ethics of taking responsibility for others: Will nuclear power increase or diminish world social injustice by concentration of power? What is the theological basis of our concern for future generations?
   c. The conditions of survival and the quality of life: are there limits to technological ventures?
   (Presentation by a theologian)

IV. SOCIAL AND ETHICAL IMPLICATIONS OF THE LONG-TERM COMMITMENT TO NUCLEAR POWER – AND THE CONTRIBUTION OF THE CHURCHES

In terms of the stages of nuclear development we are at the point of take-off. Unfortunately we do not understand sufficiently the chain of events arising out of these circumstances to be able to identify the system of international control and management that may be demanded of us in the future. It is also acknowledged that the future nuclear capacity will be beyond the scope of any group of governments or international agency, and that we have already embarked on this path without any clear means of controlling it, or of weighing its ultimate consequences for humanity at large.

The possibility exists therefore that the scale of operation and the proliferation of nuclear capacity would have consequences, because of the problem of security and safeguard, totally threatening the fabric of a democratic society as it is usually conceived. One of the proponents of nuclear power, Dr Alvin Weinberg, openly acknowledged the vulnerability of such a large-scale dependency on nuclear technology:

> "We nuclear people have made a Faustian bargain with society. On the one hand we offer... an inexhaustible source of energy. Even in the short range, when we use ordinary reactors, we offer energy that is cheaper than energy from fossil fuel. Moreover, this source of energy, when properly handled, is almost non-polluting... But the price that we demand of society for this magical energy source is both a vigilance and a longevity of our social institutions that we are quite unaccustomed to."

This problem is already evident from the secretive and defensive attitudes of the operators of nuclear power installations when publicly called to account for the integrity of their operations. These attitudes are justified because at the present moment nuclear installations are recognized to be a risk.

We are going down a path where we have no understanding of the ultimate dangers. We have been overtaken by events (e.g. nuclear weapons and political agreements to supply nuclear plants around the world) so that the areas of choice may already be limited by purely strategic considerations. It is of course within the civil sector that public opinion has most recently been activated but this may be a suitable occasion to re-open the question of the ultimate implications.

We seem to have two choices:

1. To enter the "era of hypotheticality" (W. Häfele) enjoying the benefits of increased energy supplies, and accepting the uncertainties of the present day; but at the same time imposing a largely unknown risk on our descendants;
2. to regulate the introduction of this technology on a world-scale so that it is more in line with a clearly formulated understanding of the right measure of future dependency on nuclear energy – which today is still a largely unanswered question.

The fragility of the essential system of international economic and social interdependence has widely been demonstrated in recent years; to add a further dimension of risk and uncertainty and on such a large scale would seem to compound the problem. For this reason alone we must have a further understanding of the availability and use of nuclear power systems long before the situation becomes entirely irretrievable.

There is a need to approach these questions in a truly ecumenical spirit, that is, in the concern for the welfare of all peoples. The churches can contribute to the careful examination of the long-run implications of nuclear development. Some local groups of Christians are already deeply involved in local and national study and action on the further extension of nuclear power programmes. The Hearing will seek to learn from their experience and contribute such guidance and information as may be available from the discussion of these questions at the international level.

V. PARTICIPATION, PROCEDURE, DATE AND PLACE OF THE HEARING

Participation: There will be about 25 participants – 7 or 8 theologians and lay persons (non-scientists), 10 scientists and political leaders involved in the current debate, the chairman and 6 or 7 expert witnesses. The chairman will be Prof. H.B.G. Casimir of the Netherlands, President of the European Physical Society. Dr. John M. Francis, a British nuclear physicist and Senior Research Fellow for energy studies, Heriot-Watt University (Edinburgh), who has given invaluable assistance in the preparation of this prospectus, will be rapporteur.

Procedure: The Hearing Group will meet for five days. A half day will be given to the discussion of each topic with opportunity for questions by the Hearing Group. The Hearing Group will have two and a half days to discuss its own recommendations. The following rule concerning evidence should apply to the conduct of the Hearing: no arguments may be presented which are not supported by evidence made available to all members of the Hearing Group.

Date and Place: The Hearing will take place in the Sigtuna Foundation, Sigtuna, Sweden, June 24-29, 1975, at the invitation of the Archbishop of Uppsala and the Swedish Ecumenical Council. It will constitute part of the Swedish churches' celebration of the 50th Anniversary of the first Ecumenical Conference on Life and Work, Stockholm, 1925.

SOCIAL INSTITUTIONS AND NUCLEAR ENERGY

ALVIN M. WEINBERG

Fifty-two years have passed since Ernest Rutherford observed the nuclear disintegration of nitrogen when it was bombarded with alpha particles. This was the beginning of modern nuclear physics. In its wake came speculation as to the possibility of releasing nuclear energy on a large scale: By 1921 Rutherford was saying, "The race may date its development from the day of the discovery of a method of utilizing atomic energy".[1]

Despite the advances in nuclear physics beginning with the discovery of the neutron by Chadwick in 1932 and Cockcroft and Walton's method for electrically accelerating charged particles, Rutherford later became a pessimist about nuclear energy. Addressing the British Association for the Advancement of Science in 1933, he said: "We cannot control atomic energy to an extent which would be of any value to do so".[2] Yet Rutherford did recognize the great significance of the neutron in this connection. In 1936, after Fermi's remarkable experiments with slow neutrons, Rutherford wrote: "... the recent discovery of the neutron and the proof of its extraordinary transmutations at very low velocities opens up now possibilities, if only a method could be found of producing slow neutrons in quantity with little expenditure of energy".[3]

Today the United States is committed to over 100 x 10^6 kilowatts of nuclear power, and the rest of the world to an equal amount. Rather plausible estimates suggest that by 2000 the United States may be generating electricity at a rate of 1000 x 10^6 kilowatts with nuclear reactors. Much more speculative estimates visualize an ultimate world of 15 billion people, living at something like the current U.S. standards: nuclear fission might then generate power at the rate of some 300 x 10^9 kilowatts of heat, which represents 1/400 of the flux of solar energy absorbed and reradiated by the earth.[4]

This large commitment to nuclear energy has forced many of us in the nuclear community to ask with the utmost seriousness questions which, when first raised, had a tone of unreality. When nuclear energy was small and experimental and unimportant, the intricate moral and institutional demands of a full commitment to it could be ignored or not taken seriously. Now that nuclear energy is on the verge of becoming our dominant form of energy, such questions as the adequacy of human institutions to deal with this marvellous new kind of fire must be asked, and answered, soberly and responsibly. In these remarks I review in broadest outline where the nuclear energy enterprise stands and what I think are its most troublesome problems; and I shall then speculate on some of the new and peculiar demands mankind's commitment to nuclear energy may impose on our human institutions.

Nuclear Burners – Catalytic and Noncatalytic

Even before Fermi's experiment at Stagg Field on December 2, 1942, reactor designing had captured the imagination of many physicists, chemists, and engineers at the Chicago Metallurgical Laboratory. Almost without exception, each of the two dozen main reactor types developed during the following 30 years had been discussed and argued over during those frenzied war years. Of these various reactor types, about five, moderated by light water, heavy water, or graphite, have survived. In addition, breeders, most notably the sodium-cooled plutonium breeder, are now under active development.

Today the dominant reactor type uses enriched uranium oxide fuel, and is moderated and cooled by water at pressures of 100 to 200 atmospheres. The water may generate steam directly in the reactor (so-called boiling water reactor (BWR)) or may transfer its heat to an external steam generator (pressurized water reactor (PWR)). These light water reactors (LWR) require enriched uranium and therefore at first could be built only in countries such as the United States and U.S.S.R., which had large plants for separating uranium isotopes.

In countries where enriched uranium was unavailable, or was much more expensive than in the United States, reactor development went along directions that utilized natural uranium: for example, reactors developed in the United Kingdom and France were based mostly on the use of graphite as moderator; those developed in Canada used D_2O as moderator. Both D_2O and graphite absorb fewer neutrons than does H_2O and therefore such reactors can be fuelled with natural uranium. However, as enriched uranium has become more generally available (of the uranium above ground, probably more by now has had its normal isotopic ratio altered than not), the importance of the natural ^{235}U isotopic abundance of 0.71% has faded. All reactor systems now tend to use at least slightly enriched uranium since its use gives the designer more leeway with respect to materials of construction and configuration of the reactor.

The PWR was developed originally for submarine propulsion where compactness and simplicity were the overriding considerations. As one who was closely involved in the very early thinking about the use of pressurized water for submarine propulsion (I still remember the spirited discussions we used to have in 1946 with Captain Rickover at Oak Ridge over the advantages of the pressurized water system), I am still a bit surprised at the enormous vogue of this reactor type for civilian power. Compact, and in a sense simple, these reactors were; but in the early days we hardly imagined that separated ^{235}U would ever be cheap enough to make such reactors really economical as sources of central station power.

Four developments proved us to be wrong. First, separated ^{235}U which at the time of Nautilus cost around $100 per gram fell to $12 per gram. Second, the price of coal rose from around $5 per

(1) "50 and 100 Years Ago", *Scientific American* 225, 10 (November 1971).

(2) J. Bartlett, *Familiar Quotations* (Little, Brown, Boston, ed. 14, 1968).

(3) E.N. da C. Andrade, *Rutherford and the Nature of the Atom* (Doubleday, Garden City, N.Y., 1964), p. 210.

(4) A.M. Weinberg and R.P. Hammond in *Proceedings of the Fourth International Conference on the Peaceful Uses of Atomic Energy* (United Nations, New York, in press); *Bulletin of the Atomic Scientist* 28, 5, 43 (March 1972).

ton to $8 per ton. Third, oxide fuel elements, which use slightly enriched fuel rather than the highly enriched fuel of the original LWR, were developed. This meant that the cost of fuel in a LWR could be, say, 1.9 mills per kilowatt hour (compared with around 3 mills per electric kilowatt hour for a coal-burning plant with coal at $8 per ton). Fourth, pressure vessels of a size that would have boggled our minds in 1946 were common by 1970: the pressure vessel for a large PWR may be as much as 8 1/2 inches thick and 44 feet tall. Development of these large pressure vessels made possible reactors of 1000 megawatts electric (MWe) or more, compared with 60MWe at the original Shippingport reactor. Since per unit of output a large power plant is cheaper than a small one, this increase in reactor size was largely responsible for the economic breakthrough of nuclear power.

Although the unit cost of water reactors has not fallen as much as optimists such as I had estimated, present costs are still low enough to make nuclear power competitive...

Water-moderated reactors burn ^{235}U, which is the only naturally occuring fissile isotope. But the full promise of nuclear fission will be achieved only with successful breeders. These are reactors that, essentially, burn the very abundant isotopes ^{238}U or ^{232}Th; in the process, fissile ^{239}Pu or ^{233}U acts as regenerating catalyst – that is, these isotopes are burned and regenerated. I therefore like to call reactors of this type *catalytic nuclear burners*. Since ^{238}U and ^{232}Th are immensely abundant (though in dilute form) in the granitic rocks, the basic fuel for such catalytic nuclear burners is, for all practical purposes, inexhaustible. Mankind will have a permanent source of supply once such catalytic nuclear burners are developed.

Most of the world's development of a breeder is centered around the sodium-cooled, ^{238}U burner in which ^{239}Pu is the catalyst and in which the energy of the neutrons is above 100×10^3 electron volts. No fewer than 12 reactors of this liquid metal fast breeder reactor (LMFBR) type are being worked on actively, and the United Kingdom plans to start a commercial prototype fast breeder by 1975. Some work continues on alternatives...

Nuclear Power and Environment

The great surge to nuclear power is easy to understand. In the short run, nuclear power is cheaper than coal power in most parts of the United States, in the long run, nuclear breeders assure us of an all but inexhaustible source of energy. Moreover, a properly operating nuclear power plant and its sub-systems (including transport, waste disposal, chemical plants, and even mining) are, except for the heat load, far less damaging to the environment than a coal-fired plant would be.

The most important emissions from a routinely operating reactor are heat and a trace of radioactivity. Heat emissions can be summarized quickly. The thermal efficiency of a PWR is 32%; that of a modern coal-fired power plant is around 40%. For the same electrical output the nuclear plant emits about 14% more waste heat than the coal plant does; in this one respect, present-day nuclear plants are more polluting than coal-fired plants. However, the higher temperature plants, such as the gas-cooled, the molten salt breeder, and the liquid metal fast breeder, operate at about the same efficiency as does a modern coal-fired plant. Thus, nuclear reactors of the future ought to emit no more heat than do other sources of thermal energy.

As for routine emission or radioactivity, even when the allowable maximum exposure to an individual at the plant boundary was set at 500 millirems (mrem) per year, the hazard, if any, was extremely small. But for practical purposes, technological advances have all but eliminated routine radioactive emission. These improvements are taken into account in the newly proposed regulations of the Atomic Energy Commission (AEC) requiring, in effect, that the dose imposed on any individual living near the plant boundary either by liquid or by gaseous effluents from LWR's should not exceed 5mrem per year. This is to be compared with the natural background which is around 100 to 200 mrem per year, depending on location, or the medical dose which now averages around 60 mrem per year.

As for the emissions from chemical reprocessing plants, data are relatively scant since but one commercial plant, the Nuclear Services Plant at West Valley, New York, has been operating, and this only since 1966. Dating this time, liquid discharges have imposed an average dose of 75 mrem per year at the boundary. Essentially no ^{131}I has been emitted. As for the other main gaseous effluents, all the ^{85}Kr and ^{3}H contained in the fuel has been released. This has amounted to an average dose from gaseous discharge of about 50 mrem per year.

Technology is now available for reducing liquid discharges, and processes for retaining ^{85}Kr and ^{3}H are being developed at AEC laboratories. There is every reason to expect these processes to be successful. Properly operating radiochemical plants in the future should emit no more radioactivity than do properly operating reactors – that is, less than 10% of the natural background at the plant boundary.

There are some who maintain that even 5 mrem per year represents an unreasonable hazard. Obviously there is no way to decide whether there is any hazard at this level. For example, if one assumes a linear dose-response for genetic effects, then to find, with 95% confidence, the predicted 0.5% increase in genetic effect in mice at a dose of, say, 150 mrem would require 8 billion animals. At this stage the argument passes from science into the realm of what I call trans-science, and one can only leave it at that.

My main point is that nuclear plants are indeed relatively innocuous, large-scale power generators if they and their subsystems work properly. The entire controversy that now surrounds the whole nuclear power enterprise therefore hangs on the answer to the question of whether nuclear systems can be made to work properly; or, if faults develop, whether the various safety systems can be relied upon to guarantee that no harm will befall the public.

The question has only one answer: there is no way to guarantee that a nuclear fire and all of its subsystems will never cause harm. But I shall try to show why I believe the measures that have been taken, and are being taken, have reduced to an acceptably low level the probability of damage.

I have already discussed low-level radiation and the thermal emissions from nuclear systems. Of the remaining possible causes of concern, I shall dwell on the three that I regard as most important: reactor safety, transport of radioactive materials, and permanent disposal of radioactive wastes.

Avoiding Large Reactor Accidents

One cannot say categorically that a catastrophic failure of a large PWR or a BWR and its containment is impossible. The most elaborate measures are taken to make the probability of such occurrence extremely small. One of the prime jobs of the nuclear community is to consider all events that could lead to accident and by proper design to keep reducing their probability however small it may be. On the other hand, there is some danger that in mentioning the matter one's remarks may be misinterpreted as implying that the event is likely to occur.

Assessment of the safety of reactors depends upon two rather separate considerations: prevention of the initiating incident that would require emergency safety measures; and assurance that the emergency measures, such as the emergency core cooling, if ever called upon, would work as planned. In much of the discussion and controversy that has been generated over the safety of nuclear reactors, emphasis has been placed on what would happen if the emergency measures were called upon and failed to work. But to most of us in the reactor community, this is secondary to the question: How certain can we be that a drastic accident that calls into play the emergency systems will never happen? What one primarily is counting upon for the safety of a reactor is the integrity of the primary cooling system: that is, on the integrity of the pressure vessel and the pressure piping. Excruciating pains are taken to assure the integrity of these vessels and pipes. The watchword throughout the nuclear reactor industry is *quality assurance:* every piece of hardware in the primary system is examined, and reexamined, to guarantee insofar as possible that there are no flaws.

Nevertheless, we must deal with the remote contingency that might call the emergency system into action. How certain can one be that these will work as planned?

Three barriers prevent radioactivity from being released: fuel element cladding, primary pressure system, and containment shell. In addition to the regular safety system consisting primarily of the control and safety rods, there are elaborate provisions for preventing the residual radioactive heat from melting the fuel in the event of a loss of coolant. In the BWR there are sprays that spring into action within 30 seconds of an accident. In both the PWR and BWR, water is injected under pressure from gas-pressurized accumulators. In both reactors there are additional systems for circulating water after the system has come to low pressure, as well as means for reducing the pressure of steam in the containment vessel. This latter system also washes down or otherwise helps remove any fission products that may become airborne.

In analyzing the ultimate safety of a LWR, one tries to construct scenarios – improbable as they may be – of how a catastrophe might occur and then one tries to provide reliable countermeasures for each step in the chain of failures that could lead to catastrophe. The chain conceivable could go like this. First, a pipe might break, or the safety system might fail to respond when called upon in an emergency. Second, the emergency core cooling system might fail. Third, the fuel might melt, might react also with the water, and conceivably might melt through the containment. Fourth, the containment might fail catastrophically, if not from melt itself, then from missiles or overpressurization, and activity might then spread to be public. There may be other modes of catastrophic failure – for example, earthquakes or acts of violence – but the above is the more commonly identified sequence.

To give flavor of how the analysis of an accident is made, let me say a few words about the first and second steps of this chain. As a first step, one might imagine failure of the safety system to respond in an emergency, say, when the bubbles in a BWR collapse after a fairly routine turbine trip. Here the question is not that some safety rods will work and some will not, but rather that a common mode failure might render the entire safety system inoperable. Thus if all the electrical cables actuating the safety rods were damaged by fire, this would be a common mode failure. Such a common mode failure is generally regarded as impossible, since the actuating cables are carefully segregated, as are groups of safety rods, so as to avoid such an accident. But one cannot *prove* that a common mode failure is impossible. It is noteworthy that on September 30, 1970, the entire safety system of the Hanford-N reactor (a one-of-a-kind water-cooled, graphite-moderated reactor) did fail when called upon; however, the backup samarium balls dropped precisely as planned and shut off the reactor. One goes a long way toward making such a failure incredible if each big reactor, as in the case of the Hanford-N reactor, has two entirely independent safety systems that work on totally different principles. In the case of BWR, shutoff of the recirculation pumps in the all but incredible event the rods fail to drop constitutes an independent shutoff mechanism, and automatic pump shutoff is being incorporated in the design of modern BWR's.

The other step in the chain that I shall discuss is the failure of the emergency core cooling system. At the moment, there is some controversy whether the initial surge of emergency core cooling water would bypass the reactor or would in fact cool it. The issue was raised recently by experiments on a very small scale (9-inch-diameter pot) which indeed suggested that the water in that case would bypass the core during the blow-down phase of the accident. However, there is a fair body of experts within the reactor community who hold that these experiments were not sufficiently accurate simulations of an actual PWR to bear on the reliability or lack of reliability of the emergency core cooling in a large reactor.

Obviously the events following a catastrophic loss of coolant and injections of emergency coolant are complex. For example, one must ask whether the fuel rods will balloon and block coolant channels, whether significant chemical reactions will take place, or whether the fuel cladding will crumble and allow radioactive fuel pellets to fall out.

Such complex sequences are hardly susceptible to a complete analysis. We shall never be able to estimate everything that will happen in a loss-of-coolant accident with the same kind of certainty with which we can compute the Palmer series or even the course of the ammonia synthesis reaction in a fertilizer plant. The best that we can do as knowledgeable and concerned technologists is to present the evidence we have, and to expect policy to be based upon informed – not uninformed – opinion.

Faced with questions of this weight, which in a most basic sense are not fully susceptible to a yes or no scientific answer, the AEC has invoked the adjudicatory process. The issue of the reliability of the emergency core cooling system is being taken up in hearings before a special board drawn from the Atomic Safety and Licensing Board Panel. The record of the hearings is expected to contain all that is known about emergency core cooling systems and to provide the basis for setting the criteria for design of such systems.

Transport of Radioactive Materials

If, by the year 2000, we have 10^6 megawatts of nuclear power, of which two-thirds are liquid metal fast breeders, then there will be 7,000 to 12,000 annual shipments of spent fuel from reactors to chemical plants, with an average of 60 to 100 loaded casks in transit at all times. Projected shipments might contain 1.5 tons of core fuel which has decayed for as little as 30 days, in which case each shipment would generate 300 kilowatts of thermal power and 75 megacuries of radioactivity. By comparison, present casks from LWR's might produce 30 kilowatts and contain 7 megacuries.

Design of a completely reliable shipping cask for such a radioactive load is a formidable job. At Oak Ridge our engineers have designed a cask that looks very promising. As now conceived, the heat would be transferred to air by liquid metal or molten

salt; and the cask would be provided with rugged shields which would resist deformation that might be caused by a train wreck. To be acceptable the shipping casks must be shown to withstand a 30-minute fire and a drop from 30 feet onto an unyielding surface.

Can we estimate the hazard associated with transport of these materials? The derailment rate in rail transport (in the United States) is 10^{-6} per car mile. Thus, if there were 12,000 shipments per year, each of a distance of 1000 miles, we would expect 12 derailments annually. However, the number of serious accidents would be perhaps 10^{-4} to 10^{-6}-fold less frequent; and shipping casks are designed to withstand all but the most serious accident (the train wreck near an oil refinery that goes into flames as a result of the crash). Thus the statistics – between 1.2×10^{-3} and 1.2×10^{-3} serious accidents per year – at least until the year 2000, look quite good. Nevertheless the shipping problem is a difficult one and may force a change in basic strategy. For example, we may decide to cool fuel from LMFBR's in place for 360 days before shipping: this reduces the heat load sixfold, and increases the cost of power by only around 0.2 mill per electric kilowatt hour. Or a solution that I personally prefer is to cluster fast breeders in nuclear power parks which have their own on-site reprocessing facilities.[5] Clustering reactors in this way would make both cooling and transmission of power difficult; also such parks would be more vulnerable to common mode failure, such as acts of war or earthquakes. These difficulties must be balanced against the advantage of not shipping spent fuel off-site, and of simplifying control of fissile material against diversion. To my mind, the advantages of clustering outweigh its disadvantages; but this again is a trans-scientific question which can only be adjudicated by a legal or political process, rather than by scientific exchange among peers.

By the year 2000, according to present projections, we shall have to sequester about 27,000 megacuries of radioactive wastes in the United States; these wastes will be generating 100,000 kilowatts of heat at that time...

The wastes will include about 400 megacuries of transuranic alpha emitters. Of these, the ^{239}Pu with a half-life of 24,400 years will be dangerous for perhaps 200,000 years.

Can we see a way of dealing with these unprecedentedly treacherous materials? I believe we can, but not without complication.

There are two basically different approaches to handling the wastes. The first, urged by W. Bennett Lewis of Chalk River,[6] argues that once man has opted for nuclear power he has committed himself to essentially perpetual surveillance of the apparatus of nuclear power, such as the reactors, the chemical plants, and others. Therefore, so the argument goes, there will be spots on the earth where radioactive operations will be continued in perpetuity. The wastes then would be stored at these spots, say in concrete vaults. Lewis further refines his ideas by suggesting that the wastes be recycled so as to limit their volume. As fission products decay, they are removed and thrown away as innocuous nonradioactive species; the transuranics are sent back to the reactors to be burned. The essence of the scheme is to keep the wastes under perpetual, active surveillance and even processing. This is deemed possible because the original commitment to nuclear energy is considered to be a commitment in perpetuity.

There is merit in these ideas; and indeed permanent storage in vaults is a valid proposal. However, if one wishes to perpetually rework the wastes as Lewis suggests, chemical separations would be required that are much sharper than those we now know how to do; otherwise at every stage in the recycling we would be creating additional low-level wastes. We probably can eventually develop such sharp separation methods; but these, at least with currently visualized techniques, would be very expensive. It is on this account that I like better the other approach which is to find some spot in the universe where the wastes can be placed forever out of contact with the biosphere. Now the only place where we know absolutely the wastes will never interact with man is in far outer space. But the roughly estimated cost of sending wastes into permanent orbit with foreseeable rocket technology is in the range of 0.2 to 2 mills per electric kilowatt hour, not to speak of the hazard of an abortive launch. For both these reasons I do not count on rocketing the wastes into space.

This pretty much leaves us with disposal in geologic strata. Of the many possibilities – deep rock caverns, deep wells, bedded salt – the latter has been chosen, at least on an experimental basis, by the United States and West Germany. The main advantages of bedded salt are primarily that, because salt dissolves in water, the existence of a stratum of bedded salt is evidence that the salt has not been in contact with circulating water during ecologic time. Moreover, salt flows plastically; if radioactive wastes are placed in the salt, eventually the salt ought to develop the wastes and sequester them completely.

These arguments were adduced by the National Academy of Sciences Committee on Radioactive Waste Management[7] in recommending that the United States investigate bedded salt (which underlies 500,000 square miles in our country) for permanent disposal of radioactive wastes. And, after 15 years of discussion and research, the AEC about a year ago decided to try large-scale waste disposal in an abandoned salt mine in Lyons, Kansas. If all goes as planned, the Kansas mine is to be used until A.D. 2000. What one does after A.D. 2000 would of course depend on our experience during the next 30 years (1970 to 2000). In any event, the mine is to be designed so as to allow the wastes to be retrieved during this time.

The salt mine is 1000 feet deep, and the salt beds are around 300 feet thick. The beds were laid down in Permian times and had been undisturbed, until man himself intruded, for 200 million years. Experiments in which radioactive fuel elements were placed in the salt have clarified details of the temperature distribution around the wastes, the effect of radiation on salt, the migration of water of crystallization within the salt, and so on.

The general plan is first to calcine the liquid wastes to a dry solid. The solid is then placed in metal cans, and the cans are buried in the floor of a gallery excavated in the salt mine. After the floor of the gallery is filled with cans, the gallery is backfilled with loose salt. Eventually this loose salt will consolidate under the pressure of the overburden, and the entire mine will be rescaled. The wastes will have been sequestered, it is hoped, forever.

(5) A.M. Weinberg, "Demographic Policy and Power Plant Siting", Senate Interior and Insular Affairs Committee, Symposium on Energy Policy and National Goals, Washington, D.C., October 20, 1971.

(6) W.B. Lewis, *Radioactive Waste Management in the Long Term* (DM-123, Atomic Energy of Canada Ltd., Chalk River, July 13, 1971).

(7) *Disposal of Solid Radioactive Wastes in Bedded Salt Deposits* (National Academy of Sciences – National Research Council, Washington, D.C., 1970; *Disposal of Radioactive Wastes on Land* (Publication 519, National Academy of Sciences – National Research Council, Washington, D.C., 1957); *Report to the U.S. Atomic Energy Commission* (National Academy of Sciences – National Research Council, Committee on Geologic Aspects of Radioactive Waste Disposal, Washington, D.C., May 1966).

Much discussion has centered around sequestration of just how certain we are that the events will happen exactly as we predict. For example, is it possible that the mine will cave in and that this will crack the very thick layers of shale lying between the mine and an aquifer at 500 feet below the surface? There is reason to suggest that this will not happen and I believe most, though not all geologists who have studied the matter agree that the 500-foot-thick layer of shale above the salt is too strong to crack so completely that water could invade the mine from above.

But man's interventions are not so easily disposed of. In Kansas there are some 130,000 oil wells and dry holes that have been drilled through these salt infusions. These holes penetrate aquifers and in principle they can let water into the mine. For the salt mine to be acceptible, one must plug all such holes. At the originally proposed site there were 30 such holes; in addition, solution mining was practised nearby. For this reason, the AEC recently authorized the Kansas State Geological Survey to study other sites that were not peppered with man-made holes. The AEC also announced recently its intention to store solidified wastes in concrete vaults, pending resolution of these questions concerning permanent disposal in geologic formations.

Man's intervention complicates the use of salt for waste disposal; yet by no means does this imply that we must give up the idea of using salt. In the first place, such holes can be plugged, though this is costly and requires development. In the second place, let us assume the all but incredible event that the mine is flooded – let us say 10,000 years hence. By that time, since no new waste will be placed in the mine after A.D. 2000, all the highly radioactive waste-decaying species, notably ^{90}Sr and ^{137}Cs would have decayed. The main radioactivity would then come from the alpha emitters. The mine would contain 38 tons of ^{239}Pu mixed with about a million tons of nonradioactive material. The plutonium in the cans is thus diluted to 38 parts per million; since plutonium is, per gram, 10,000 times more hazardous than natural uranium in equilibrium with the daughters, these diluted waste materials would present a hazard of the same order as an equal amount of pitchblende. Actually, the 38 tons of ^{239}Pu is spread over 200 acres. If all the salt associated with the ^{239}Pu were dissolved in water, as conceivably could result from total flooding of the mine, the concentration of plutonium in the resulting salt solution would be well below maximum permissible concentrations. In other words, by virtue of having spread the plutonium over an area of 200 acres, we have to a degree ameliorated the residual risk in the most unlikely event that the mines are flooded.

Despite such assurances, the mines must not be allowed to flood, especially before the ^{137}CS and ^{90}Sr decay. We must prevent man from intruding – and this can be assured only by man himself. Thus we again come back to the great desirability, if not absolute necessity in this case, of keeping the wastes under some kind of surveillance in perpetuity. The great advantage of the salt method over, say, the perpetual reworking method, or even the aboveground concrete vaults without reworking, is that our commitment to surveillance in the case of salt is minimal. All we have to do is prevent man from intruding, rather than keeping a priesthood that forever reworks the wastes or guards the vaults. And if the civilization should falter, which would mean, among other things, that we abandon nuclear power altogether, we can be almost (but not totally) assured that no harm would befall our recidivist descendants of the distant future.

Social Institutions – Nuclear Energy

We nuclear people have made a Faustian bargain with society. On the one hand, we offer – in the catalytic nuclear burner – an inexhaustible source of energy. Even in the short range, when we use ordinary reactors, we offer energy that is cheaper than energy from fossil fuel. Moreover, this source of energy, when properly handled, is almost non-polluting. Whereas fossil fuel burners must emit oxides of carbon and nitrogen, and probably will always emit some sulfur dioxide, there is no intrinsic reason why nuclear systems must emit any pollutant – except heat and traces of radioactivity.

But the price that we demand of society for this magical energy source is both a vigilance and a longevity of our social institutions that we are quite unaccustomed to. In a way, all of this was anticipated during the old debates over nuclear power. As matters have turned out, nuclear weapons have stabilized at least the relations between the superpowers. The prospects of an allout Third World War seem to recede. In exchange for this atomic peace we have had to manage and control nuclear weapons. In a sense, we have established a military inadvertent use of nuclear weapons, which maintains what *a priori* seems to be a precarious balance between readiness to go to war and vigilance against human errors that would precipitate war. Moreover, this is not something that will go away, at least not soon. The discovery of the bomb has imposed an additional demand on our social institutions. It has called forth this military priesthood upon which in a way we all depend for our survival.

It seems to me (and in this I repeat some views expressed very well by Atomic Energy Commissioner Wilfrid Johnson) that peaceful nuclear energy probably will make demands of the same sort on our society, and possibly of even longer duration. To be sure, we shall steadily improve the technology of nuclear energy; but, short of developing a truly successful thermo-nuclear reactor, transport of radioactive materials, and waste disposal. And even if thermonuclear energy proves to be successful, we shall still have to handle a good deal of radioactivity.

We make two demands. The first, which I think is the easier to manage, is that we exercise in nuclear technology the very best techniques and that we use people of high expertise and purpose. Quality assurance is the phrase that permeates much of the nuclear community these days. It connotes using the highest standards of engineering design and execution; of maintaining proper discipline in the operation of nuclear plants in the face of the natural tendency to relax as a plant becomes older and more familiar; and perhaps of managing and operating our nuclear power plants with people of higher qualification than were necessary for managing and operating non-nuclear power plants; in short, of creating a continuing tradition of meticulous attention to detail.

The second demand is less clear, and I hope it may prove to be unnecessary. This is the demand for longevity in human institutions. We have relatively little problem dealing with wastes if we can assume always that there will be intelligent people around to cope with eventualities we have not thought of. If the nuclear parks that I mention are permanent features of our civilization, then we presumably have the social apparatus, and possibly the sites, for dealing with our wastes indefinitely. But even our salt mine may require some small measure of surveillance if only to prevent men in the future from drilling holes into the burial grounds.

Eugene Wigner has drawn an analogy between this commitment to a permanent social order that may be implied in nuclear energy and our commitment to a stable, year-in and year-out social order when man moved from hunting and gathering to agriculture. Before agriculture, social institutions hardly required the

long-lived stability that we now take so much for granted. And the commitment imposed by agriculture in a sense was forever: the land had to be tilled and irrigated every year in perpetuity; the expertise required to accomplish this task could not be allowed to perish or man would perish; his numbers could not be sustained by hunting and gathering. In the same sense, though on a much more highly sophisticated plane, the knowledge and care that goes into the proper building and operation of nuclear power plants and their subsystems is something that we are committed to forever, so long as we find no other practical energy source of infinite extent.[8]

Let me close on a somewhat different note. The issue I have discussed here – reactor safety, waste disposal, transport of radioactive materials – are complex matters about which little can be said with absolute certainty. When we say that the probability of a serious reactor incident is perhaps 10^{-8} or even 10^{-4} per reactor per year, or that the failure of all safety rods simultaneously is incredible, we are speaking of matters that simply do not admit of the same order of scientific certainty as when we say it is incredible for heat to flow against a temperature gradient or for a perpetuum mobile to be built. As I have said earlier, these matters have transscientific elements. We claim to be responsible technologists, and as responsible technologists we give as our judgement that these probabilities are extremely – almost vanishingly – small; but we can never represent these things as certainties. The society must then make the choice, and this is a choice that we nuclear people cannot dictate. We can only participate in making it. Is mankind prepared to exert the eternal vigilance needed to ensure proper and safe operation of its nuclear energy system? This admittedly is a significant commitment that we ask of society. What we offer in return, an all but infinite source of relatively cheap and clean energy, seems to me to be well worth the price.

[8] Prof. Friedrich Schmidt-Bleck of the University of Tennessee pointed out to me that the dikes of Holland require a similar institutional commitment in perpetuity.

HYPOTHETICALITY AND THE NEW CHALLENGES: THE PATHFINDER ROLE OF NUCLEAR ENERGY

WOLF HÄFELE

To those who for many years have been active in the promotion of nuclear energy, the opposition of the public to the large-scale application of peaceful nuclear energy has come as a surprise. The experience of public hearings and face-to-face discussions with the opponents of nuclear energy has made them aware of modes of thought and criteria of judgement which they had not encountered previously. It is now necessary to reflect on these alternative modes of thought and judgement in order to arrive at new ones, and, by so doing, to improve the basis for rational action.

Further, it appears that these alternative modes of thought and judgement and the responses which should be called forth by them do not arise on the occasion of large-scale uses of peaceful applications of nuclear energy alone. They are only adumbrations of a broader and more general development in thinking about science and technology. In this paper, I attempt to exemplify this development. I will begin with a brief account of the development of nuclear energy.

The Development of Nuclear Energy

The development of the peaceful applications of nuclear energy was related to its military applications in various degrees which changed with the times and which were different in various parts of the world. Originally basic scientific and technological research was to the forefront. But, more and more, the technological problems of large nuclear components, facilities and plants were the ones which attracted both scientists and engineers and funds for research and development. It was from this development of nuclear energy that the phenomenon of "big science" emerged as a new form of scientific organisation and as a new category of thought about science policy. The use of nuclear power for the production of electricity had to be competitive with fossil fuels, which in the 1950s and 1960s were temporarily cheap. It was thought that even if nuclear power turned out not to be fully competitive, fossil power would continue to be available inexpensively and in any amount desired. The drive for the development of nuclear power came also from an unquestioned belief in the desirability of technological innovation. This was particularly the case in the highly industrialised states without nuclear weapons.[1]

The order or the Oyster Creek nuclear power plant given to the General Electric Company by the Jersey Central Power and Light Company promoted the commercial breakthrough towards nuclear power. Since then, 150,000 MWe have been firmly ordered, have been under construction or in operation in the United States. The corresponding figures for Germany and Japan are 13,000 MWe and 15,000 MWe. Practically all of these are light water reactors (LWR's). In Great Britain and France, experience in the design, construction and operation of gas-cooled, graphite-moderated reactors, which demonstrates a remarkable technological capacity, has been considerable. However, it was not possible to translate this experience into a commercially feasible operation.

The development of reactors must be accompanied by the establishment of a fuel industry, the operation of which is commercially feasible. Since fuel elements have to be available prior to the operation of power plants, such a nuclear fuel industry is now being established. The problem here is the minimum size of the fabrication plant. To meet this requirement a single fabrication plant has to serve several thousand megawatts of nuclear power plant capacity. For many decades, enrichment will continue to be necessary since the present nuclear power plants make use of enriched uranium. Thus far, the gaseous diffusion process has been demonstrated as technologically and economically feasible. In the years to come, such feasibility may also be expected for the centrifuge process. In addition, the nozzle process must be mentioned. Again, a large capacity of nuclear power plants to be served is required to make enrichment a practical economic undertaking.

After irradiation in such nuclear power plants, the spent fuel elements must be chemically reprocessed; such reprocessing is therefore a late step. Again, for commercial feasibility, the power plant capacity must be several thousand megawatts. The number of commercial reprocessing plants in operation today is still very small. Their technological feasibility has been demonstrated in the past, even though the scale of these demonstrations was limited. If reprocessing is to be done on a very large scale, the feedback into the ecosphere will also be very large. This, in my judgement, will lead to an extension of today's technology. This extension does not appear to be a problem of technological feasibility: it is a matter of effort and of funds.

If chemical reprocessing is a late step, the final stage of waste disposal is an even later one. If very large-scale reprocessing probably requires an extension of today's technology, this – to say the least – also holds for the technology of the disposal of final waste. Disposal in adequately selected salt mines seems a suitable approach to this problem, and demonstration plants are being operated today.[2]

The picture of the peaceful application of nuclear energy for the economically competitive production of electricity is, therefore, today rather a simple one. LWR nuclear power plants are commercially feasible and are being installed and operated on a large scale. Those parts of the nuclear fuel cycle which must be carried out prior to, or at the same time as, the start of the operation of power plants are now commercially feasible also. Those parts of the nuclear fuel cycle which come into the picture only after the combustion of fuel elements require, in my judgement,

[1] Häfele, Wolf and Seetzen, Jürgen, "Prioritäten der Grossforschung" in Grossner, Claus, *et al.* (eds.), *Das 198. Jahrzehnt: Eine Team-Prognose für 1970 bis 1980* (Hamburg: Christian Wegener Verlag, 1969), pp. 407-435; Servan-Schreiber, Jean-Jacques, *Le Défi Américain* (Paris: Denoël, 1967).

[2] Wittenzellner, R., "Storage of Solid Radioactive Waste", and Tuohny, T., "Managing Liquid Radioactive Waste", discussions on the storage of nuclear waste, 20 September, 1973, at the 17th Regular Annual Session of the IAEA General Conference, Vienna, 18-24 September, 1973.

an extension of present-day technology. The later they come into the process, the more they require the extension; such an extension is feasible. If, in the past, the nuclear power plant was the main target for research and development, in the future it will be that part of the fuel cycle which, in time, is last.

A similarly positive assessment can be made for commercial ships operating under nuclear power. The United States, the Soviet Union, Germany, and, soon also, Japan have or will have demonstrated the successful operation of such ships.

Only 10 years ago the picture was by no means as clear. There was an overwhelmingly large variety of competing types of nuclear power plants and the various features of the fuel cycle were not so readily discernible. There are now essentially two types of nuclear power plants which have evolved as second generation counterparts of the LWR. These are the high temperature, gas-cooled reactor, and the fast breeder reactor. I need not elaborate on the technical details, but will observe only that high temperature, gas-cooled reactors are capable of providing nuclear power at temperatures of 1,000°C. and more. This has certain advantages if electricity is to be produced. But the main thing is that, by virtue of high temperatures, nuclear power becomes applicable as chemical process heat. This means an extension of nuclear power beyond the production of electricity. In order to appreciate this feature fully one must realise that only roughly 25 per cent of the total demand for primary energy is a demand for the production of electricity. The remaining 75 per cent go in roughly equal parts into the sectors of transportation, domestic, and other industrial uses. The advantage of the high temperature, gas-cooled reactor is that it can make nuclear power applicable to these sectors.

The fast breeder reactor places the provision of fuel for nuclear power on a completely different basis. Fast breeder reactors extract on average roughly 100 times more energy from a given amount of natural uranium than can other nuclear reactors, including the high temperature, gas-cooled reactor. In the short term, this results in a remarkable stability in the price of uranium ore. At present ore prices, only one thousandth of the cost of generating electricity arises from the provision of ores. As a result, almost any uranium price can be afforded. This implies that even those ores which are of average richness can be processed. In the long run, this leads to a situation where nuclear power is capable of providing enough energy for several hundred thousand, if not million, years. The LWR of today can do that only for some decades. Both the high temperature reactor and the fast breeder complement the LWR remarkably well, and strategies can be identified which will ease the transition from market situations in the present day to world-wide problems of energy demand and supply in the future.[3]

In discussing the present position of nuclear energy, the element of time must be emphasised. The development of nuclear energy originally had a highly complex and sometimes disturbing appearance. Consideration of the temporal aspect led to a process of selection, in the course of which the valid parts of this development became evident. Those who were involved had to be educated and again this required time. For instance, it was through a step-by-step process that the electricity-producing firms – and national laboratories too – came to understand how to act in the development of nuclear power. Over and above all this, there is an inherent temporal dimension to such complex technological and organisational developments.

Large and complex developments have to pass over three thresholds. The first of these is the threshold of scientific feasibility: in the development of nuclear power for peaceful applications, the principal step towards scientific feasibility was taken by Enrico Fermi as early as 1943. The definitive consolidation of these steps occurred between 1943 and 1950. The second threshold is that of technological and industrial feasibility: to pass this threshold is a step the size of which is often underestimated. In the development of light water reactors in the United States this step comprised the successful establishment and operation of the Dresden, Yankee, and Indian Point – roughly 200 MWe – demonstration plants; in Western Germany, the plants at Obrigenheim and Lingen performed this function. The significance of operating these demonstration plants only began to be clearly evident in the early 1960s. In other words, it required nearly two decades to pass from the threshold of scientific feasibility to the threshold of technological and industrial feasibility. Fast breeder reactors and high temperature, gas-cooled reactors are passing the latter threshold only now.

The third threshold is that of economic and commercial feasibility. As a result of its complexity. This appears to be the most difficult threshold to those who have lived through the various stages of such a development. Let us recall that there were quite a number of reactor types which were technologically and industrially feasible but which were unable to pass over the third threshold. This is true for instance of the gas-cooled, graphite-moderated, natural uranium reactors which were developed in the United Kingdom and France. Economic and commercial feasibility implies that industry is able to sell its product at competitive prices without public subsidy. It also requires that the utility companies must be able and willing to place orders necessary for such very large-scale industrial projects and that the governmental bodies must have taken the necessary regulatory measures. It is this last step which turns out to be of outstanding importance. In the United States and, for instance, in Western Germany, acceptance of their appropriate roles and responsibilities by the various partners involved has been a long and sometimes complicated process.

Even now, about 30 years after Enrico Fermi's historic accomplishment, the process has not come to an end. The larger public has recently begun to realise the dimensions of this development. It is assuming a role in the third stage of the development which it did not accept in the first two phases. The objections to nuclear power which have been raised by certain parts of the larger public must therefore be taken seriously and fully understood.

Objections to Peaceful Nuclear Energy

These objections have arisen during recent years not only in the United States but also in Western Germany, Sweden, Switzerland, the Netherlands and Japan. It may be observed in passing that such opposition has not taken place – or at least not to such an extent – in Canada, the United Kingdom, France, Italy, and certain other countries. Generally speaking, the main objections to peaceful nuclear power appear to be the following: (1) the routine operation of nuclear power plants creates dangers of radiation; (2) if nuclear power is produced on a large scale, it is impossible to exclude the risk of a major accident, resulting in even greater dangers of radiation; (3) since fissile material can be used for both peaceful and non-peaceful purposes, there is a risk, in handling large amounts of fissile material, of the illegal diversion of such fissile material; (4) the operation of nuclear power plants necessi-

[3] Häfele, Wolf and Schikorr, Winfried, "Reactor Strategies and the Energy Crisis" IAEA Study Group on Reactor Strategy Calculations, Vienna, 5-9 November, 1973.

tates the storage and disposal of radioactive wastes for periods of time which exceed human experience; (5) the large-scale operation of nuclear power plants involves the handling of large amounts of plutonium which must be kept out of the ecosphere; (6) the operation of nuclear power plants results in the production of large amounts of waste heat; (7) the erection of nuclear power plants requires too much land; and (8) the demand for more energy which is to be met by nuclear power is not real but is a product of manipulation.

These objections must be met. Many writers have been doing this over the past few years,[4] but this is not the task to which I am addressing myself in this paper. Rather, I wish to reflect on these arguments and to consider them in new categories, which will allow for a better understanding not only of the objections but also of the answers. To this end, I will consider more specifically a few of the objections.

The Routine Operation of Nuclear Power Plants: Today's routine operation of nuclear power plants leads to a radiation danger which is smaller than 5m rem/year. Recently it has also been made mandatory for LWRs to make the radiation danger smaller than 5m rem/year; the regulation said "as low as practicable". The question now is whether such a limit is acceptable. Originally the regulatory limit was 170m rem/year, but the practice was not to exceed 5m rem/year. A large margin therefore evolved. Dr. Gofman and Dr. Tamplin then made it a point to argue that not only the practical value but the regulatory limit as well should be correspondingly low. Their argument was as follows: there is experimental evidence to show that applying 1 rem induces about 20 additional cases of leukaemia per million persons. The relevant experiments were made at about 50 rem or more. If all kinds of cancer besides leukaemia are taken into account, the figure may be as high as 120 persons per rem per million persons. Then they calculated the number of cases of cancer by straightforward algebra, considering only 0.17 rem/year (i.e., 170m rem/year) and 200 million persons (equalling the population of the United States). This leads to $17 \cdot 10^{-2} \times 2 \cdot 10^{-8} \times 120 \times 10^{-6} \sim 4{,}000$ additional cases of cancer. Their conclusion was that this figure is too high.[5] A tremendous public debate resulted with much talk about the effects of poisonous nuclear power. It also led to new regulations by which a formal interpretation of the wording "as low as practicable" was required. The regulation now provides that the radiation danger be smaller than 5m rem/year.[6] This figure leads to 120 cases instead of 4,000.

The question necessarily arises: why is that the right figure? There is of course no answer to this. One cannot argue in the domain of absolute figures – comparisons by means of a yardstick are the only reasonable procedure. Such a yardstick can only come from placing the problem in the setting of nature. The "natural" radiation is, on average, 120m rem/year. The variation of that figure is high. Changing positions on the surface of the earth can easily lead to an increase of 50m rem/year. This is the case if one moves, for example, from Pittsburgh to the Smoky Mountains in the United States. Similarly, living in a concrete building leads to an increase of roughly 20m rem/year. In view of both, the average value and the variation of the natural radiation, 5m rem/year is a small figure. "Embedding" the problem into the normal conditions of life therefore does provide a yardstick. Similarly, one should make the comparison with the number of cancer cases which ordinarily occur. In the United States, there are 300,000 cases per year, so it is this figure against which the additional number of 4,000, or 120, as the case may be, must be assessed.

Many of the opponents of nuclear energy now say that statistical considerations are inhuman, and that any additional life which is "willingly" sacrificed is too much. Human beings have names. But this argument, by virtue of the simple algebra given above, implies a causal relation between the additional 5m rem/year and the additional 120 cases of cancer. While experimental evidence for this causal relation can be demonstrated, at the level of 50 rem, i.e., the ten-thousandfold value, this is certainly not the case at 5m rem. It is a problem of the extrapolation to low rates of dosage. Such an extrapolation is very hypothetical because there is no way of proving it experimentally. Further, such re-extrapolation requires that all other parameters be held constant. There is no individual, with a name, for whom this can be done. It is obvious that entering the hypothetical domain leads into strenuous debates which become so animated because they can never be resolved. "Embedding" is the way out of this dilemma. The normal conditions of life provide a yardstick or standard.

The International Committee on Radiological Protection (ICRP) deals with standards by establishing limits of radiological dosage on an international basis. This requires understanding the causal relations between rates of dosage and damage. Understanding these causal relations, however, is only one side of the coin. The other side of the coin is the standard of what is acceptable. This, too, is done through the process of "embedding". The ICRP shows it is aware of this by making the following observation:

Any exposure to radiation is assumed to entail a risk of deleterious effects. However, unless man wished to dispense with activities involving exposures to ionizing radiations, he must recognize that there is a degree of risk and must limit the radiation dose to a level at which the assumed risk is deemed to be acceptable to the individual and to society in view of the benefits derived from such activities.[7]

"Embedding" entails the establishment of a criterion which incorporates both of the actions recommended – in this case, the erection and operation of nuclear power plants – and the benefits and risks of the alternatives. The most straightforward way of doing this is to consider the ratio. Up to now, the ICRP has refrained from identifying the denominator of that ratio, the benefit, on the grounds that the benefit varies from society to society and from one situation to another. The assessment of radiation standards in a situation of oil shortage, for instance, is one thing; considering

[4] See, for instance, "The Nuclear Controversy in the USA", International Workshop, Lucerne, Switzerland, 30 April-3 May, 1972, sponsored by the Swiss Association for Atomic Energy in cooperation with the United States Atomic Industrial Forum; and "Energie und Umwelt Informationsdienst der Zeitschrift", which appears in each issue of *Atomwirtschaft – Atomtechnik*.

[5] Actually, the figure which Drs. Gofman and Tamplin were talking about referred to 30,000 persons, because they employed a different set of medical data. But this does not influence the logic of the argument presented here. Gofman, J.W. and Tamplin, A.R., *Poisoned Power: The Case against Nuclear Power Plants (Emmäus, Pennsylvania: Rodall Press, 1971).*

[6] United States Atomic Energy Commission, "Proposed Rule Making, Licensing of Production and Utilization Facilities. Light-Water-Cooled Nuclear Power Reactors. /10 CFR Part 50/", *Federal Register,* XXXVI, 111 (June 1971). See also, United States Atomic Energy Commission, "As Low as Practicable Numbers could end the Radiation Controversy...", *Nucleonics Week,* XII, 22 (June 1971), p. 4.

[7] ICRP, "Recommendations of the International Commission on Radiological Protections", *ICRP Publication,* pt. 9, A(34) (Oxford: Pergamon Press).

such standards in a situation where large amounts of very inexpensive energy exist is another. In addition, benefits may appear differently to poor countries and rich ones. For these reasons, the ICRP decided to leave the evaluation of such benefits, and therefore the ratios of benefits to risks, to the respective national bodies.

There is a further point: the ICRP talks of risks. There is little doubt that if the process of radiation damage were completely understood it would be possible to assess that radiation damage deterministically. Damage could be assessed with certainty. Risks of the kind we are discussing refer to events governed by laws of nature of which we have incomplete knowledge.[8] If our knowledge were complete, the ratio in question would become a ratio of benefit to damage. The problem would not be one of the acceptability of risks but of the acceptability of damages which are certain. In either case, it is acceptability which is at issue.

Comparing risks – or damage – arising from a proposed activity with those occurring in nature is one way of dealing with the problem of acceptability. Another way is to ask for alternatives to the activity proposed. For instance, are there alternative possibilities of producing sufficient amounts of energy at prices which purchasers are willing to pay? Such alternatives are features of the world we live in and this also might therefore be viewed as "embedding". For some time to come the possibility of energy production by the combustion of fossil resources will remain. For the moment we will leave aside the problem of the adequacy of resources. The point here is rather that the use of fossil fuel is also accompanied by pollutants which damage health. The most notable is SO_2. Of course a Gofman-Tamplin analysis can be made here too. It has been reported that for every 100 persons-ppm-year, there is roughly one death which is a result of respiratory infection.[9] In larger cities, SO_2 concentrations in the order of 100 $\mu g/m^3$ of SO_2 can often be observed. This relates to the order of 0.1 ppm. Making the assumption here that about 60 million persons in the United States live in areas of such SO_2 content, this results in $6 \cdot 10^7 \cdot 0.1 \cdot 10^{-2} = 60{,}000$ deaths/year as a result of SO_2. The problem raised by Drs. Gofman and Tamplin is therefore not peculiar to nuclear energy. It can always be raised when low rates of dosage of any toxin or drug are considered. Needless to say, in the case of SO_2, as in that of radiation, the question of the causal relationship must be considered. Again we enter the domain of the hypothetical.

For each of the various pollutants, such as SO_2, a standard must be established; the analogous problem of the establishment of radiological standards must then be treated in the same manner. This immediately raises the problem of how we can ensure that all the standards in question are equally rigorous. The question necessitates a comparison of risks – or damage – of completely different kinds. How does pollution by SO_2 add to that of dust, and does the sum of both compare to 5 mrem/year? The difficulty is, however, broader than that. How is a dusty atmosphere related to a risk of having a 1/2 per cent increase in the rate of mutation within a few generations? The time element complicates the issue even further.

Up to now the approach to these questions has been implicit or pragmatic. In the past this was satisfactory because the related issues were of limited size and therefore of limited significance. But in the life of coming generations, with the increased use of technology which produces more pollution and the prospect of a greatly increased population and a greater demand for energy, this becomes a question of much greater urgency. It is necessary therefore to look for methods to approach these problems in a more coherent and systematic way. Furthermore, the interest of mathematicians in these problems has helped to make for a greater awareness of the possibility of treating the problems more systematically through the use of concepts like the value problem, vector, value optimisation, the decision process, and others.[10] The problem of the evaluation of risk raises basic methodological problems. Only very little knowledge is available,[11] and much work is required in this field.

The task may be formulated in summary form along the following lines: it is necessary to establish standards for the impacts of certain technological measures. In doing this we will contribute to the evaluation of related problems. The establishment of standards entails relating, as thoroughly as possible, ambient rates of dosage to physiological and other damage. At the same time, we must establish criteria and rules of acceptability, including both damage which is certain and the risk of damage. This requires "embedding" the standards and criteria into the normal conditions of life. For the evaluation of alternatives, it is necessary to establish standards of a completely different nature. This inherently requires their comparison and involves a process of decision, i.e. a problem of value.

Rare but Major Accidents: Nuclear power plants are made to be safe on the basis of passive or active engineering measures. This means that engineering measures either act by their mere existence – for example, as shields and locks – or by positive action – for example, as moveable control rods. Any such engineering measure can fail and in an advanced state of technology it is possible to assess a probability of such failures. This has been done in electronics in particular. While small, such probabilities of failure are nevertheless finite. If the probability of failure is considered to be too high, a second line of defence has to be installed. Safety components must be installed which are redundant. By the successive staging of such safety devices, it is possible to make the probability of failure smaller than any given small number[12]; but it is not possible to reduce it completely to zero. This, then, raises a number of problems. The first of such problems was stated by Dr. Starr as "How safe is 'safe enough'?" In recent years, the concept of failure rates has been introduced. A rate of failure of, for example, 10^{-x} per year, might be considered. For instance, x could be between 3 and 7. This leads into the intricate problem, which is partly a semantic one: is a plant of a failure rate of 10^{-7} really 10 times safer than a plant of 10^{-6}? If the term "safe" is clearly defined by such failure rates, this is certainly so. But is this definition adequate? What is the more general meaning of "safe" to a wider public? And can such a more general meaning really be quantified?

[8] This is a general observation. See the recent discussion of this problem in Brooks, Harvey, "Science and Trans-science", in Correspondence, *Minerva,* X, 3 (July 1972), pp. 484-486.

[9] Wilson, R., "Tax the Integrated Pollution Exposure", *Science,* CLXXVIII, 4057 (October 1972), pp. 182-183.

[10] Raiffa, Howard, *Decision Analysis: Introductory Lectures on Choices under Uncertainty* (Reading, Mass.: Addison-Wesley, 1968).

[11] See, for instance, Starr, Chauncey, "Benefit-Cost Studies in Socio-Technical Systems", Colloquium on Benefit-Risk Relationships for Decision-Making, Washington, D.C., 26-28 April, 1971, sponsored by the United States National Academy of Engineering. See also, Otway, Harry and Erdmann, Robert, "Reactor Siting and Design from a Risk Viewpoint", *Nuclear Engineering Design,* 13 (1970), p. 365.

[12] Häfele, Wolf, "Ergebnis und Sinn des SEFOR Experiments", in Scheibe, E. and Süssman, G. (eds.), *Einheit und Vielfalt, Festschrift für C.F. von Weizsäcker zum 60. Geburtstag,* (Göttingen: Vandenhoeck and Ruprecht, 1972), p. 248.

When we ask "How safe is 'safe enough'?" we are again led into the process of "embedding". Other risks have to be considered and alternatives have to be evaluated. Solar power and geothermal energy resources must be considered and compared with nuclear power. These alternatives have their own risks. If the residual risk of operating a nuclear power plant is to be compared with these risks, one has to reflect on the fact that the residual risk in the case of nuclear power is not a risk to be considered without reference to alternatives. There is little doubt that the laws of nature which are employed in the design and operation of, for example, a control rod are quite adequately understood. But, for the application of these laws of nature, knowledge of all initial and boundary conditions is also required. These initial and boundary conditions are not part of the laws of nature but are required if the laws of nature are to be applied to a particular case. This is necessarily so. The generality of the laws of nature results from the abstraction of the elements of the actual case, which are the initial and boundary conditions. As an example, let us think of the differential equation for a mechanical movement. Newton's law is general and governs all mechanical movements. But if the fall of a particular apple from a particular tree is to be predicted, the locus and the momentum of the apple at a given moment in time must be provided.

Measurement is the only way to accomplish this. This is a principal observation. The difference between the nature of initial and boundary conditions and the laws of nature has been dealt with recently by Professors Carl Friedrich von Weizsäcker and Erhard Scheibe,[13] who have described the nature of initial and boundary conditions as contingent. In so doing, they employ the medieval philosophical term contingere, which is a translation by Boethius of the more basic Greek word ἐνδέχομαι. It means encountering an event without being able to predict it; it simply happens. In this context, my usage of the word "contingent" is different from the common English word "contingent", which has a somewhat different meaning but which has the same root. Leaving aside the still more basic problem of interpretations in quantum theory, one must make the further observation that it is impossible to measure initial and boundary conditions with the completeness and accuracy necessary for a fully deterministic prediction of the performance of a technical component or device. This is where risk resides. It is not a risk of the type which is related to uncertainties in the knowledge of the employment of the laws of nature. It is a risk of the kind which refers to incomplete knowledge of initial and boundary conditions. While, at least in principle, it is possible to eliminate risks of the first kind, there is no possibility of doing so with risks of the latter kind. We can always improve our knowledge about contingent elements, but we can never make it complete. This restates the proposition that the residual risk can be made smaller than any given small number but it cannot be reduced to zero.

The traditional engineering approach to eliminating risks of the second kind – the risks which are integral to contingency – is trial and error. The engineer learns by experience to make better and safer machines. This is close to the scientific approach: an hypothesis is made which is followed by experiments, which in turn lead to an improved hypothesis, which again is followed by experiments. In this way a theory evolves which is true, i.e., is in touch with reality: *Veritas est adequatio rei et intellectus.*[14] It is precisely this interplay between theory and experiment, or trial and error, which is no longer possible for new technologies which are designed to master unique challenges. In the case of reactor safety this is obvious. It is not acceptable to learn reactor safety by trial and error. Before we continue this line of reasoning, another observation is in order.

Reactor engineers face this dilemma by dividing the problem of engineered reactor safety into sub-problems. For instance, the integrity of a pressure vessel is investigated as a sub-problem, and so is the operability of control rods and pumps. To use the performance of such components to draw conclusions about the performance of the whole nuclear plant of course requires a certain preconceived idea of the various interactions which must be considered when the components are combined. In combining such components more contingent elements come into the picture. The aim is to minimise the impact of incomplete knowledge of contingent elements. Therefore, in designing the needed experiments – which are tests, in this context – the largest possible units are sought. But, by the same token, the generality of the conclusion is reduced just because it was the contingent elements which led to these tests of large technological units. In persisting further and further along this line of reasoning, one arrives at a situation where the truly large-scale test can only result in the statement that a given device functioned at a particular time and place. A general conclusion is impossible. Because of the fact that the test stressed the contingent aspect of the elements, all generality is eliminated. Reactor engineers are familiar with this feature of reality. To some extent, the term "integral test" refers to it. We should recall the debate on the advisability of reactor tests of the Borax type,[15] where the argument was raised that almost nothing general could be concluded from such an integral test. Only large instrumentation could justify such an expensive test. But this refers exactly to the measurement of contingent elements. At the extreme, one may call such large-scale integral tests "happenings".

Let us again return to the general line of the reasoning followed in this paper. Reactor safety in its ultimate meaning cannot be evaluated by trial and error. Subdividing the problem can lead only to an approximation to ultimate safety. The risk can be made smaller than any small but predetermined number which is larger than zero. The remaining "residual risk" opens the door into the domain of "hypotheticality". At this stage, it becomes clearer that the concept "hypotheticality" is crucial in this analysis. A few words of explanation are therefore necessary. Hypotheticality, of course, is not a word in regular usage but its logic expresses precisely what must be expressed in the line of reasoning presented here. Its logic is the same as that of the word "criticality", for example, a term which is familiar to reactor engineers. The rule followed is that for Latin words ending in *-itas,* for example, *veritas* or *felicitas.* Such substantives point to features which exist in principle and which if actualised, lead to the fact that something can have a certain property: a reactor can become critical or a situation can be considered to be hypothetical. The process of iteration between theory and experiment which leads to truth in its traditional sense is no longer possible. Such truth can no longer be fully ex-

[13] von Weizsäcker, Carl F., "Komplementarität und Logik", *Die Naturwissenschaften,* XLII, 19 (1955), p. 521. See also Scheibe, Erhard, *Die kontingenten Aussagen in der Physik* (Frankfurt: Athenäum, 1964), and *The Logical Analysis of Quantum Mechanics* (Oxford: Pergamon Press, 1973).

[14] Aquinas, Thomas, *Quaestiones disputatae de veritate,* verit 1. 1c. This formula has been widely referred to in the history of medieval philosophy and stresses the objectivity of things.

[15] Dietrich, Joe R., "Experimental Determination of the Self-Regulation and Safety of Operating Water-Moderated Reactors", *Proceedings International Conference on Peaceful Uses of Atomic Energy,* August 1955, Geneva, United Nations, New York, vol. 13 (1956), pp. 88-101.

perienced. This means that arguments in the hypothetical domain necessarily and ultimately remain inconclusive. I think that this ultimate inconclusiveness which is inherent in our task explains, to some extent, the peculiarities of the public debate on nuclear reactor safety. The strange and often unreal features of that debate, in my judgement, are connected with the "hypotheticality" of the domain below the level of the residual risk.

Why is it impossible to apply the method of trial and error to ultimate reactors safety? It is impossible because the consequences of so doing would be too far-reaching. Every country is too small for that – eventually even the globe itself is too small. The magnitude of the technological implications thus becomes comparable with the magnitude of the constraints which determine our normal life. This inapplicability of the scheme of trial and error may be regarded as a kind of cost – or risk. But nuclear power is to be justified by its capacity to provide practically infinite amounts of energy for even a highly populated and industrialised world. This is an unusual kind of benefit which exceeds any so far experienced. The appropriate concern therefore is whether the ratio of such costs and benefits is adequate. To complete the picture, the magnitude of engineered safeguards also is inherently very large, and is hitherto unexperienced. The inverse failure rates which relate to the periods of time within which to wait for a failure are an indication of that. The magnitude of the constraints of the world we live in corresponds, if properly interpreted, with the magnitude of the costs – or risks – the magnitude of the engineering measures needed to guard against it, and the magnitude of the benefits.

In dealing with reactor technology, we should realise that nothing less than this is at stake. I think that it is insufficient to look at nuclear power plants as mere substitutes for the present more conventional power plants which use fossil fuels.[16] In line with this reasoning, it is perfectly legitimate to look for alternatives to nuclear power. These alternatives must, however, be evaluated by means of the same global standards or within the same magnitude and scope as nuclear power. To give an example: Tidal power is not an alternative. It cannot provide the same amount of power as can nuclear power.[17] If nuclear power proves superior to other alternatives when properly evaluated, it will be fully legitimate to proceed with what will then be the truly large-scale development of nuclear power.

Let us for a moment consider some of these choices. As mentioned before, one such alternative is solar power. At first inspection, solar power appears to be a clean source of energy. Solar power has, however, the disadvantage of being dispersed; one cannot hope to harvest more than, say, $20W/m^2$. Large areas of the globe must therefore be utilised to provide very large amounts of solar energy. The present consumption of energy in the world is at $8 \cdot 10^{12}W$; in the future, $60\text{-}150 \cdot 10^{12}W$ must be prepared for, as the world population increases and the poorer countries begin to obtain their share. A figure of $100 \cdot 10^{12}W$ at $20W/m^2$ implies a figure of $5 \cdot 10^{12}\ m^2$. This is about 20 times the area of the German Federal Republic. To take such a step might not be impossible eventually but its size and nature imply a kind of impact on the normal conditions of life – including the political aspects of such normal conditions – which indeed offers little advantage over the impact of other alternatives. If produced on a very large scale, solar power would not offer a solution which left the normal conditions of life unchanged.

There are other repercussions of the development of solar power besides the use of very large tracts of land. The energy balance of the atmosphere above these large areas would of course change accordingly. One has to realise that such changes would be likely to happen in stages. The most probable first stage would be a change in the pattern of rainfall, but not in the global average of the amount of rainfall. Even if nothing else were to happen, there would be dramatic consequences: the continuous drought in North Africa which we experience today is indicative of that. In the next stage, the average amount of rainfall and its pattern would alter together with regional changes in climate. One result might be a regional change of average temperatures and winds. In the third stage, the global climate would change with a change in the average global temperature. This could cause an ice-age or melting of ice-caps. It is not good enough to point out that even large-scale harvesting of solar energy would make up only 1 per cent. or so of the total solar input and might therefore be negligible. The question is more delicate than this since regional instabilities of weather and climate are at stake. It is equally inadequate to point out that regional uses of solar power are desirable and clean in many if not all respects. Only if solar power can be produced on a very large scale can it be considered to be a legitimate alternative to nuclear power. It may very well be the case that eventually a combination of solar, nuclear and possibly even other additional forms of energy might turn out to be the optimal condition. I mentioned earlier that a major effort is now under way to develop comprehensive computer programmes for the largest computers available, and to develop appropriate global systems for monitoring weather conditions, pollutants, and other parameters such as the CO_2 content of the air.[18] This will bring significant progress. But it will always be impossible to run truly integral experiments as they were discussed above in the case of nuclear reactor safety. The prediction of man's impact on the climate will never be fully proved experimentally, or, to be more exact, by trial and error. The magnitude of the risk which is involved again corresponds to the magnitude of the constraints which determine our normal life. A residual risk will therefore remain. Again one finds oneself in the domain of "hypotheticality" and the debate on the related issues will be inconclusive.

It is now clear that a similar argument holds for the very large-scale "harvesting" of the heat in the earth's crust. This statement implies, among other things, that the risk of inducing large-scale earthquakes is unacceptable. Furthermore, contrary to a widespread belief, the fusion reactors which are hoped for would by no means be a source of clean power.[19] More systems-analyses comparing various alternatives for the provision of energy are now urgent, although it is unlikely that one of the alternatives would turn out to be clearly superior to all others.

The ecological impact of human activities is also of that nature. Once ecological equilibria are destroyed, it takes periods of time beyond human experience for their re-establishment. In this case, too, trial and error, or, rather, the iteration of theory and experiment, cannot provide a definitive solution. Residual risks will remain.

[16] Weinberg, Alvin, private communication.

[17] See, for instance, Hubbert, M.K., "The Energy Resources of the Earth", *Scientific American*, CCXXV, 3 (September 1971), p. 60.

[18] World Meteorological Organisation and International Council of Scientific Unions, "The First GARP Global Experiment, Objectives and Plans", *GARP Publication Series*, nr. 11 (March 1973).

[19] Häfele, Wolf and Starr, Chauncey, "A Perspective on Fusion and Fission Breeders", *Journal of the British Nuclear Energy Society (forthcoming)*.

Many more examples of this situation can be found. The tasks which we confront in the assessment of nuclear power are prototypical of a wider range of emerging problems; in this sense, the analysis of the problems of nuclear power is a pathfinding undertaking. If properly interpreted and understood, the public concern about nuclear power is not unfounded. But that concern is not a simple function of a peculiarity of nuclear power. It is, rather, the general condition of civilisation towards which we are moving; it is a condition where the magnitude of human enterprises becomes comparable with the magnitude of the widest determinants of our normal existence. Nuclear power turns out to be a forerunner, a pathfinder, of that.

Nuclear Material Safeguards: Another objection raised by the opponents of nuclear power asserts that it will render easier the illegal diversion of nuclear material for military purposes. This is sometimes called the problem of safeguards. A vast international effort has been made to deal with the problem. The conception, negotiation and commencement of the Treaty on the Non-Proliferation of Nuclear Weapons marked a great step forward in this respect. A major effort of systems-analysis and development led to the establishment of the safeguards system of the International Atomic Energy Agency (IAEA). The continued operation of the European Atomic Energy Community as well as the United States Atomic Energy Commission safeguard systems have also contributed to a considerable reduction of the risk of illegal diver sion.

As in other situations in which risks of catastrophic dimensions must be dealt with, so in the case of safeguards also the establishment of standards was in the forefront of interest. In order to establish thresholds of significance, it was necessary to obtain experimental values for the material unaccounted for (MUF), since the accountability of nuclear material is the corner-stone of the present safeguard systems. The side of the task which deals with causal relations of a scientific or technological nature was more or less readily taken care of. To that end a number of experiments were designed and executed. The result was that the amount of MUF for the various nuclear facilities such as reprocessing plants was established. On the other side, it was necessary to reflect on the demands for such accountability. Was the IAEA system of safeguards to be designed to account for kilogrammes, grammes, or milligrammes of nuclear material? And what were the periods of time during which the detection of diversion had to take place? It was a painful and lengthy process to explain to politicians that it would be impossible to account for absolutely all the nuclear material. A residual percentage would go into MUF; there was bound to be a residual risk in the case of safeguards, as in other situations of the kind under discussion.

What then is acceptable? In the case of international safeguards against the illegal diversion of nuclear material, the need to accept residual risks has led to highly hypothetical considerations. One such hypothetical problem was whether it would be considered feasible that someone should drill little holes into thick concrete walls for the diversion of x grammes of uranium. The domain of the hypothetical comes even more clearly into focus if I report here on the concern that there might be someone in a hidden back room in the basement of a power plant preparing plutonium without paying attention to any radiation this might cause. As a result of an intensive international effort under the guidance of IAEA for several years, it was eventually possible to narrow the gap between the demand for international safeguards and their feasibility. It was possible to assess the acceptability of residual risks. Yet absolute certainty of the safeguards cannot be provided; a residual risk remains and therefore the situation is "open-ended".

The responses which can be given to those who object to the development and use of nuclear power are pretty much the same for all the arguments. There is one exception. This is the argument which asserts that the demand for energy is the result of manipulation and is not "real". It is an interesting question, but it does not involve scientific or technical considerations of the kind which I have been treating in this paper. Hence, I shall not deal with it here.

Marginal Remarks on the Energy Problem

It nevertheless seems appropriate to make a few remarks on the nature of the problem of energy which industrial countries are facing, as this establishes the scope for any systems-analytical evaluation or assessment of nuclear energy or related phenomena. It is most important to realise that the problem of energy appears in phases over time, the features of which are sometimes very different. In the first phase of the problem, it is the oil shortage which is to the forefront. This phase will last for at least 15 years because any technological measure requires that much time before its impact attains substantial economic significance. During this phase, research and development on the substitution of synthetic hydrocarbon fuels for oil are urgently needed. The second phase is likely to be characterised by the large-scale use of nuclear power in the production of electricity and of coal for the non-electrical sector of demand for secondary energy. This phase may last for a few decades.

In the long run, i.e., in the third phase, all demand for primary energy must be met by other than fossil fuels. There are four alternatives: nuclear fission energy, nuclear fusion energy, solar power, and geothermal energy from the earth's crust. All four alternatives can provide very large amounts of energy, although in different degrees.

During the second phase, preparations for changing to one of these alternatives or to a combination of them must be made. These preparations will require more than the exclusive consideration of the supply of fuel. The procedure of "embedding" is needed in order to arrive at an optimal solution. The problem of fuel supply must be "embedded" in the atmosphere, the hydrosphere, the ecological sphere and the sphere of social life. The demand for and supply of energy and their embedding have to be considered on a scale which might be something like 25 times larger than today's scale. It must be assumed that the world's population will increase and that the poor countries will begin to approximate the consumption of energy *per caput* which is close to that of the rich countries.

This, then, is the setting for assessing the various technological alternatives for providing enough energy and their various advantages and disadvantages. The promulgation and comparisons of standards, the assessment of residual risks, "hypotheticality"

[20] International Atomic Energy Agency, "The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons", IAEA, Vienna. Information Circular 153, 1971. See also, Häfele, Wolf, "Systems Analysis in Safeguards of Nuclear Material", *Proceedings Fourth International Conference on Peaceful Uses of Atomic Energy*, September 1971, Geneva, United Nations, New York, IAEA, Vienna, vol. 9 (1972), p. 303.

and "embedding", are the intellectual procedures which must accompany the technological developments of tomorrow.[21]

"Hypotheticality" and Arms Control

It is probable that "hypotheticality" will characterise the next stage of human enterprise. The magnitude of technological enterprises will be so great that it will not be possible to proceed with the absolute certainty that there will be no negative consequences. The magnitude of the undertaking and the intellectual impossibility of eradicating all contingency make the prospect for "hypotheticality" even more certain. But if we are condemned to "hypotheticality", are there ways to deal with it? Most of these ways are still to be explored. The case of arms control, however, might illustrate the way of proceeding which is available to us. It was recognised in the case of nuclear armament earlier than in other spheres that it was leading into qualitatively new conditions. The yield of atomic weapons exceeded all previous experience and the means of delivering such weapons permitted delivery from almost any part of the earth's surface to almost any other part. The magnitude of the military and technological implications became comparable with the magnitude of the determinants which set the framework of our normal existence. Furthermore, it is impossible to develop the art of nuclear warfare by trial and error, as was previously always the case with innovations in military technology. Hence, residual risks became evident in the field of atomic warfare. This happened early and a number of schools of thought have evolved to deal with these residual risks and to develop a practicable rationale or doctrine.[22]

The kind of reasoning which developed in these schools of thought soon became very specialised. It was not easily possible for a citizen who was not a scientist, or even for scientists who were not working intensively in this field, to follow these developments. The debate on anti-ballistic missile systems (ABM), on multiple independently targeted re-entry vehicles (MIRV), and other such problems, demonstrated this. The reasoning involved in these decisions was extremely complicated and abstract. It was also extraordinarily difficult to propound absolutely conclusive arguments. There was always another view and there was no way of ultimately proving one's own position. At the same time, the whole domain of nuclear armament was vitally urgent. It was considered to be a matter of life and death to have a strategic doctrine which would deter one's visible and rational opponent from engaging in nuclear warfare. This feature of being extremely unreal – abstract and irrelevant – and at the same time extremely real – and relevant – developed into a serious gap in the late 1960s when the ABMs and MIRVs came into the picture. At that time SALT negotiations started. For a long period it was not clear whether a treaty would be agreed to. But even if they had not resulted in such a treaty, it would indeed have been an achievement to have held the SALT negotiations. In the course of these negotiations the two antagonistic parties talked to each other and came to understand better each other's rationale of nuclear strategy. It was a matter of enhancing the prospect of the survival of the human race. It gave a hint about how to deal with "hypotheticality".

This simultaneity of two contradictory modes of appearance is well known in the rigorous interpretations of the meaning of quantum theory. In order to overcome contradictions such as that between wave and particle modes of appearance, it was necessary to have recourse to more pronounced abstractions. Thus, it was no longer feasible to describe the laws of quantum theory – and hence the laws of nature for that matter – in the ordinary space-time domain. Only the abstract Hilbert space was feasible for the description of the laws of nature. At this level of abstraction, there was no longer a contradiction between the two modes of appearance. But the translation of statements which belong to Hilbert space in the ordinary space-time domain always leads to some kind of strange phenomena, like the principle of uncertainty, which are difficult to cope with if such abstraction is not employed.

Nuclear warfare and arms control were the first human activities which touched upon the constraints and conditions which are imposed on us by living on our finite earth. The rational treatment of nuclear warfare and arms control leads immediately into the domain of "hypotheticality" with all its peculiarities. Nuclear warfare and arms control not only touch the finite limits of the earth; they bear very intimately on our interdependent large-scale civilisation in which there are no isolated areas for instructive trial and error.

The Formalised Debate

Many of the statements and actions of the opponents of nuclear energy are wrong and even harmful. It is by no means the purpose of this article to imply that they are right. They are not. But they have led to debate and hence some of their effects must be estimated positively. These debates have positive consequences. The regulatory interpretation of the phrase "as low as practicable" in the case of LWRs is one such positive consequence. To have aroused a more acute awareness of the potential – and hypothetical – dangers is another positive result. Such results depend upon antagonists talking to each other and listening to what the other has to say. For this to happen on a large scale is not easy. But in a democratic society it must occur on a large scale because, eventually, decisions about acceptability profoundly affect every member of society. These issues are beyond the powers of science but they are of vital concern to citizens. Dr. Alvin Weinberg has called the domain of these issues "trans-science".[23] To facilitate a general debate on these issues a high level of formalisation appears to be necessary. Abstract and complex problems beyond human experience or the experience of everyday life must be dealt with.

The licensing process which is required for the construction and operation of nuclear power plants in the United States has already established such a formalised debate. The necessity of taking a position under the pressure of deadlines is very conducive to hard thought. Design engineers, including myself, have tried to come to such conclusions before the formal licensing procedure by strenuous thinking and by prior consultations with the individual members of the licensing bodies. However, these methods have not been satisfactory. Only the formalised confrontation with the antagonist's arguments, when the licensing body is acting in full responsibility, permits the kind of analysis needed for a design in a particular case.

[21] Häfele, Wolf, "Energy Systems", in *Proceedings of the IIASA Planning Conference on Energy Systems,* Laxenburg, Austria, International Institute for Applied Systems Analysis, July 1973.

[22] A well-known example is contained in Wiesner, Jerome B., "Comprehensive Arms-Limitation Systems", in *Arms Control, Disarmament and National Security* (New York: George Braziller, Inc., 1961), pp. 198-233.

[23] Weinberg, Alvin, "Science and Trans-science", *Minerva,* X, 2 (April 1972), pp. 209-222.

The treatment of particular cases by a formalised procedure for dealing with particular situations forces abstract considerations to take concrete form. All this imposes time-limits and enforces specificity and concreteness in analysis. The licensing process takes place in several rounds. It is an iterative process which usually produces convergence from diverse positions. This iterative process in time supplants the iterative scheme of trial and error: *Veritas est adequatio rei ad intellectum.*[24] It bridges the gap which is imposed on us by "hypotheticality". But formalisation goes even further. It allows a great number of parties to state their case. In a formalised debate, this accentuates the iterative process. This also tends to bridge the gap of "hypotheticality".

In this setting too, nuclear energy, by leading to this kind of a licensing process, has turned out to perform a pathfinding function. Formal licensing procedures using public hearings are now being applied to situations other than those involving nuclear energy. If in the previous paragraph on arms control it became apparent that it is the element of debate which is necessary and, further, that a stride towards more abstraction is required if one wants to meet present and future challenges, now, following the observations of this last paragraph, it seems possible to go on a step further and to identify the object of such abstraction. It is the debate itself. Procedures must be devised which permit the intangible to be made tangible. A rationale for the formalisation of the debate here envisaged must be established.[25] It appears that in this respect too nuclear energy serves as a pathfinder.

[24] This formula and similar ones have been widely used in the history of medieval philosophy to stress things as objects of comprehension, in contrast to Thomas Aquitas' formula.

[25] To some extent this is concerned with the problem of the role of scientists as advisors. This problem has been examined in *Minerva,* X, 1 (January 1972), pp. 107-157; X, 2 (April 1972), pp. 280-294; X, 3 (July 1972), pp. 439-451; X, 4 (October 1972), pp. 603-613; XI, 1 (January 1973), pp. 95-112; and XI, 2 (April 1973), pp. 228-262.

However, the point which is developed here is not exactly the problem of scientific advice. It is rather the function of science in designing the rationale of a formalised debate. The partners in such a debate can be of many different kinds. Science is not necessarily the leading partner in this.

THE SAFETY OF SAFEGUARDS

A NOTE ON PROF. HÄFELE'S PAPER

JEROME R. RAVETZ

We are frequently told that in view of the depletion of other effective sources of energy, we must develop nuclear energy if our civilisation is to survive. Here I ask whether our present and future level of civilisation is sufficiently advanced for us to use nuclear energy without putting mankind's survival at serious risk.

It is not enough to say that we "must" solve an engineering problem such as safety in civil nuclear energy. Sadder and wiser than a decade ago, we know that some engineering problems are effectively insoluble. This insolubility is, of course, relative to a set of technical, social and moral constraints. Thus, one might reconstruct a city centre to allow all commuters to drive in alone in their cars, but this would involve such total devastation of existing structures and such fantastic cost in the building of access and storage facilities that we all now admit that the problem is "effectively insoluble".

We are, therefore, at liberty to ask whether the problem of safety in civil nuclear energy is effectively soluble, given the constraints which experience can teach us. I do not wish to argue one side or the other, but only to exhibit some of those constraints. Two sorts of insight are relevant here, deriving from our experience of human beings and of nature. In each case they place the physical devices and systems in a social and moral environment with which they interact.

Since the problem of safety is largely one of control – including monitoring and, where necessary, applying corrections – my argument depends on an analysis of "safety-control" as an institutionally organised human activity. I identify three principles of rule-governed behaviour which are relevant to systems of control intended to ensure safety.

We may start with the old question: *"Quis custodiet ipsos custodes?"* – Who guards the guardians? No system of control involving human agents is self-controlling as a whole. The hierarchy of control is, in a sense, uncontrolled or open-ended at the top. No matter how many elaborate checks and sanctions are formally built into a system of control, they will operate only to the extent that there is an effective commitment for them to do so, in spite of their inherent personal costs to the controllers. We then have the principle of the "open-endedness" of such a system, and the need for commitment at the top of any hierarchy of control.

We draw the practical conclusion that there is no guarantee that the socially "best possible" system of control in a given environment will be adequate to its intended functions. In the case of the global safety of nuclear energy systems, the point might be translated into a maxim: "Do not circulate weapons-grade plutonium in a country where the chief inspectors can be bribed." Whether even this restriction would eliminate safety-control systems inadequate to their function is something about which experts might argue.

It follows from the first principle that every human control system needs a meta-system for its own control. Since this relation iterates without end, we immediately see that "ultimate" control in any human system must be informal, personal, even partly tacit. This feature of control systems interacts in practice with another property of all systems of rule-governed human behaviour, namely, that it is necessary for operatives to violate the rules sometimes in order to accomplish their assigned tasks. Instead of arguing this in detail, I will simply point to the phenomenon of disruption through "working to rule". Hence, it is strictly impossible for a control group to enforce perfect adherence by operatives to any set of formal rules. They must be allowed initiative to accomplish their tasks as they see fit. This inherent informality and imprecision of human control systems has important consequences for all work governed by standards of adequacy of results. The degree of quality which can be effectively achieved, even within a purely technical possibility, will depend on the commitment of the operatives. A management, however committed itself, cannot arbitrarily define and enforce standards. If the workforce refuses to pay the personal costs of achieving them, the standards will eventually be jettisoned in the interest of the accomplishment of more obvious goals, as formal – or formalistic – "completion" of tasks. Thus, we have the second principle: the "incompleteness" of the controllability of tasks, and the need for commitment at the bottom of the hierarchy.

Applying this principle, we see that the adequacy of any system of quality-control to its tasks depends on circumstances. There can be striking successes, as that achieved by the National Aeronautics and Space Administration; but there can also be failures, as in the badly fabricated energy-conversion plants, conventional and nuclear, in Great Britain and abroad. There is absolutely no guarantee that the desire of management, or even the need of civilisation, to have the extremely stringent standards of quality-control in the fast-breeder reactor is sufficient for their enforcement. This problem of safety-control in manufacture may be effectively insoluble.

The third principle relevant to systems of control is the "degeneration" of routine tasks. There is not enough "motivational capital" to go round, to cover the multitude of boring, repetitious tasks on the diligent accomplishment of which all monitoring – and hence safety-engineering – depends. It is no answer to "automate" them. This may reduce their quantity, but it cannot change their quality. Also, using iteration again, we see the need for the routine human task of monitoring the system of automatic control. Applying this principle, we can understand the otherwise astounding reports of lax security at American civil nuclear installations. It needs no arguing that here, as in the former two cases, the institutional, social and moral aspects of the human environment are crucial in the containment of the degenerative effects of this situation.

The importance of these principles of human behaviour in systems of control becomes clearer in the light of a principle about natural systems. It is now common knowledge that any process of manipulation of materials, or energy, or information, is part of a cycle. We must soon come to appreciate that flows in all phases of the cycle and through the boundaries of the system require individual, appropriate systems of control. This new principle is crucial in revealing the complexity, true cost, and questionable feasibility of adequate systems of safety-control for the full "nuclear cycle".

To apply this principle we must first educate ourselves away from thinking of isolated "nuclear power stations" and instead always think of "nuclear fuel cyclic systems". The transport and handling of ores, fresh fuels, spent fuels, re-processed fuels, temporary hot wastes, and permanent cooler wastes, are all essential parts of the operation of nuclear power stations. They are not accidental, unfortunate overheads on the "real" facility, which is the generating station. Of course, they obtrude in this case because the nuclear fuel cyclic system has hazards of an order unknown to fossil fuels.

When we consider the operation of such a system, we can do more than observe this or that particular hazard. On the basis of these, we can raise the question of whether the institutional, social and moral environment can sustain adequate systems of safety-control...

Nuclear reactors are – so far – unique in civil life in the degree to which the physical engineering of their matter and energy systems requires extraordinarily high standards in the social engineering of their systems of safety-control. If these fail, now or at some time in the indefinite future, life on this planet will be endangered. Yet these systems of control are vulnerable to the effect of "open-endedness" of control at the top, "incompleteness" of controllability of tasks at the bottom, and to the "degeneration" of routine monitoring tasks. In these respects the tasks of safety-control of civil nuclear energy are peculiarly sensitive to the quality of the civilisation in which they are located.

Relative to the constraints of society as we now have it, even at its best, the problem of safety in civil nuclear energy might be effectively insoluble. In this strong dependence of the physical system on its cultural environment, we may have a very practical example of the frequently lamented imbalance between our material powers and moral progress up to now.

A "REFLECTION" PAPER ON NUCLEAR ENERGY POLICY IN HOLLAND

INTRODUCTORY NOTE ON THE DUTCH NUCLEAR DEBATE IN 1974

In late 1974 the discussion about the expansion of nuclear power in the Netherlands, one of the most densely populated countries in the world, has made headlines in the Dutch newspapers. Previously it had been package news, going along the lines familiar to most countries: a few scientific dissenters at the start, with the public debate slowly catching up.

There are two reasons for the recent excitement: (1) Several thousands of Dutch people refused to go on paying a 3% tax on their electricity bill to be used to fund a multi-national project for an experimental fast breeder reactor; (2) a first draft of a long overdue energy policy paper by the coalition government was leaked and itrevealed plans for an expansion of nuclear power plants from 500 MWe to 3500 MWe in the coming 10 years.

Holland has been slow in developing nuclear power because it has large indigenous natural gas reserves. In addition to two small experimental reactors, only one commercial reactor (477 MWe) has been operating since 1973. A second commercial nuclear power plant of 600 MWe has been considered since 1971, and two industrial groups, each including Dutch and foreign partners, had been asked to make bids for this plant.

The draft government paper of 1974 mentioned a "modest expansion" of three 1000 MWe power stations before 1985. Worried by the shallow arguments given for this expansion a group of 23 concerned people sat together and prepared a "reflection" paper on nuclear energy policy in Holland. The group included journalists, members of four government parties and concerned scientists, including several from industry. In their paper they ask for a five-year reflection period before Holland proceeds to build more commercial nuclear power plants. (The word moratorium was purposely not used as it is little known in Dutch and "reflection" was more in line with the groups' quest for a serious rethinking of the basics of national growth and energy planning.) The group does not consider itself anti-nuclear. Their common denominator is their concern over the government's arguments for taking an immediate decision on the expansion of nuclear power in this densely populated country.

To influence policy making in the council of ministers the reflection paper was issued to the Dutch press on September 10, 1974, a week before the final discussion was supported by 33 important scientists and leading theologians (both Protestants and Catholics). All these persons supported the concept of the paper without necessarily agreeing with every detail. They have agreed upon the proposal for a five-year period of reflection on the expansion of commercial nuclear power stations in Holland.

The paper made headlines and the publication of the government energy paper was postponed several weeks. Once published it showed a compromise. No longer were the three 1000 MWe nuclear plants definite; but there was a decision in principle to have them operating in 1985. First, however, several studies on health, safety and siting aspects had to be completed, due June 1st, 1975.

The date for starting construction also roused controversy. While the Minister of Economic Affairs proposed 1976 as the latest possible date, the Prime Minister favoured 1979 in a private letter to concerned party members. Since then most political parties and trade unions have voiced concern over the government plans and requested more studies before the final decision is taken.

The reflection paper also aroused criticism, mainly from the utilities and the industrial organizations. They claimed the paper underestimated the potential of Dutch industry in the nuclear field and was too pessimistic on the economic benefits of nuclear generated electricity.

At the end of October 1974 the Dutch Parliament discussed the nuclear chapter of the government's energy paper and extracted from the Minister of Economic Affairs a promise that no construction programmes would be initiated until the Parliament has had the opportunity to discuss each of the promised studies on safety, health, siting, etc.

For all parties affected this implies an armed status quo for at least a year until these studies will come into the discussion. In the meantime the ad hoc "Reflection Group" (as it has become known) will continue to work on several studies: e.g. the real costs of electricity from different systems, employment aspects of the nuclear option and some non-nuclear scenarios for Holland.

"REFLECTION" PAPER – NUCLEAR ENERGY

OPTIMAL POLICY CHOICE

Now that two nuclear plants are already in production in the Netherlands and the experimental fast-breeding nuclear reactor at Kalkar (FRG) under construction, it has become necessary to choose the best means for the future supply of electricity in our country.

The choice has to be made from among the following alternatives:

(a) To resolve that a substantial proportion of the future generation of electricity will come from nuclear energy, with future planning based on this premise.

(b) To build a number of nuclear plants over the next ten years with, as the prime objective, the accumulation of experience in this sector, with the strict understanding, however, that after perhaps five years, a new choice is to be made between alternatives (a) and (b) for discontinuation/continuation of nuclear energy as potential power source.
In support of this decision, investigations will be carried out on the subject of power supply.

(c) For the time being (up to a period of five years) to halt the further construction of nuclear power plants and during this time,

to permit only the construction of fossil-fuelled plants. Simultaneously, to undertake a detailed programme of investigations with the exclusive aim of determining the best method of providing the supply of energy.

(d) To dispense now with nuclear energy as a form of power supply.

The choice has to be made **now**, in a situation where the following features should be taken into consideration:

- It is generally acknowledged that the knowledge available on nuclear power systems falls short in a great many areas; or, what amounts to the same thing, the experts disagree violently with each other on a multitude of subjects. This conflict of opinion extends not only into such areas as the risk analysis (emergency, cooling, theft, sabotage, blackmail, waste disposal, ecological hazards, etc.), but also extends through to the much more down-to-earth subject of the actual economic price per kilowatt hour of the **total nuclear power system.**
- For a number of reasons in the wake of the "oil crisis", all of the more long-term forecasts on power consumption have become extremely uncertain. While many **savings** are already being introduced using existing technology, intensive efforts are being made to discover new methods for economizing on power consumption, and these will most certainly be implemented in the future.

A further consideration is that the extremely rapid growth in energy consumption in the Netherlands[1] has been caused by a one-sided expansion in the industrial sector. From many quarters a more balanced growth has been called for. Only after an industrial plan has been drawn up, will it be possible, on the basis of the resulting investments, to make definite forecasts of energy requirements.

This has become even more crucial now in the light of new questions being raised as to the boundaries within which social development should be confined, as well as to the broad aims of our society.

Discussion on the nature and desirability of continued, but selective, economic growth is well underway.[2]

- The "oil crisis" has lent strong impetus to the search for **new methods of providing energy.**
- **The decision-making mechanism** in this country is undergoing improvement, especially with regard to democratization and the selection of the broad policy outlines for long-term planning (e.g. long-term budgets, the formation of the Scientific Council for Government Policy in 1972).
- **Public opinion** is at present divided, and agitated by the uncertainty regarding the available and generally accepted knowledge on nuclear energy.

All these phenomena tend to make for an extremely difficult situation in which to make the right decisions, decisions which in the long run will limit the options for our society.

The above characteristics are not entirely unchangeable. If all efforts are combined, it is very possible that within a period of five years there could be a general, in some cases considerable, improvement, i.e. better insight and knowledge, better planning, more consensus of opinion, more clearly defined objectives, better methods, etc., and this in turn will promote a much more responsible attitude towards the necessary decision-making for long-term policy planning.

Optimal planning at the present time entails choosing the alternative which provides for:

1. lowest possible cost to society
2. guaranteed future provision of electricity
3. reduction in Holland's dependence on other countries, especially those outside the E.E.C.
4. improvement in employment opportunities
5. structural support to industry
6. amassing a store of knowledge, at the moment not available on energy problems, especially where this is vital to planning
7. enhancement of healthy urban planning
8. the avoidance of unnecessary and unknown risks
9. contribution to a situation in which public opinion regarding energy provision can be on the basis of awareness of the facts
10. maximum freedom of choice for planning in the future.

Using these ten points as a basis, the above-mentioned alternatives (a) and (d), which imply a definite decision become void. This narrows down the field to alternatives (b) and (c), and in the following pages we will deal with the choice between these two remaining alternatives as they affect the above ten aims.

1. Costs

It is generally believed that, with present prices, electricity generated from nuclear energy would be cheaper than that generated by fossil-fuelled plants. The lower price is a result of the correlation between much higher capital costs and much lower fuel prices.

This means that in its initial stages, a nuclear power plant places a larger drain on the national product than a fossil-fuelled plant of the same capacity. The advantages of the lower fuel costs of a nuclear power plant would only result in a lower total cost after a number of years (using the cash flow method[3], a reasonable estimate is about five years following commencement of production).

Using the discounted cash flow method, this effect would be achieved much later on because the advantage of fuel cost for a nuclear power plant is discounted more severely, and furthermore, due to the longer preparation and construction time, the start-up capital must be provided earlier on.

[1] The annual energy growth rate has been an average 7% in the last ten years.

[2] In the last two years several governmental, political and scientific reports have appeared in Holland which questioned economic growth. Most of these called for a fundamental discussion on what is called "selective growth" policies; one of these reports is soon to appear in English: *New Scarcity and Economic Growth* by R. Hueting (Liverpool University Press, 1975).

[3] In the U.S. serious speculation has arisen about the financial side of nuclear energy. Until 1980, $ 18 to 25 billion per year will be needed to finance the effort. A national council of financing bodies, energy experts and consumer advisors has been set up for this purpose. There is also a definite trend visible in the U.S. towards stalling the extension of the nuclear power network because of these financial consequences. In 1980 there are supposed to be 40 plants of 1000 MW ready, but construction has not yet started on any of them. *(AEC News Release* No. 32, Vol. 5, August 7, 1974.

No allowance has yet been made here for a number of cost elements for nuclear power plants.[4]

Furthermore, the nuclear plant system causes a number of costs[5] for society as a whole, costs which cannot be quantified at present. If the government assumes responsibility for these costs instead of incorporating them into the electricity tariffs, one arrives at a false cost comparison.

Option (b) (experimental nuclear power plants) will certainly not entail lower total expenses than option (c) in the first 15 years, but it will carry higher start-up costs. Furthermore, the possibility must not be ignored that if the construction of nuclear power plants is going to continue throughout the world, under option (c) the opportunity will probably arise for the selection of standardized, quantity-produced power plants of known and tested design, whereby sizeable savings in installation and operating costs may be obtained. This in comparison with option (b), whereby one is committed to participate in each separate stage of the development.

2. The Certainty of Electricity Supply

Under option (c) (exclusive planning of fossil-fuelled plants until 1980) this is a known certainty. Means of checking in some measure the demand for electricity are known, just as the extent of the availability of prime energy sources to meet a curbed demand is known. Certainly, the requisite investments should be made in good time for exploration and development of new oil and gas fields.

Under option (b) (introduction of nuclear power plants on an experimental basis) the problem of large investments is even more critical. Added to this is the risk of teething troubles occuring in a sketchily tried and tested technology[6] – including the possible risk of a serious nuclear disaster happening somewhere in the world and as a result, widespread public outcry against nuclear energy as a fuel source.

Breakdown in a nuclear power plant resulting from anyone of these causes could have serious repercussions for both the economy and the employment situation. Under option (c) much more will be known in five years' time about the reliability of this source of power and the public's reaction to it; besides which, at that time one will be able to choose from various types of tested, quantity-produced nuclear plants.

3. Dependence on Other Countries

Option (b) implies that we would be placed in a particularly precarious position as far as dependence on other countries is concerned. In the short run, there is a shortage of enrichment capacity; the available reprocessing possibilities are minimal; which country would take our waste? We need time to make the necessary arrangements for these things before we commit ourselves irreversibly to nuclear energy.

As far as the western world's dependence on the OPEC countries is concerned, there is little difference between options (b) and (c).

The construction of nuclear reactors and isotope separation units demands large quantities of energy.[7] This means that in the expected "lean oil years" up to 1985 there will be little influence on the total amount of fossil fuel required.

4. Employment Opportunity

With option (c), by far the largest part of funds destined for research and for fossil-fuelled plants will be spent in the Netherlands. With options (b), only a modest part of the funds for design and construction of nuclear plants will be assigned to Dutch firms.

Between 1975 and 1980, option (c) will impose a smaller drain on the National Product. In order to arrive at a true comparison of influence on employment opportunity, it must be assumed that due to extra government assignments outside the electricity sector (or due to lowering of tax levels) similar amounts will be apportioned to options (b) and (c). Option (c) (lower import share) therefore means a greater contribution to employment opportunity.

With option (b) the possibility remains that after five years further implementation of nuclear power will be halted. Yet employment opportunity at that particular point in time will be keyed to a programme of further expansion. This means therefore that option (b) (if truly made) poses a danger for employment possibilities following cessation of the trial period.

5. Industrial Investment and Know-How

Option (b) forces Dutch industry into a fairly sizeable investment programme for specialized apparatus and task forces of qualified manpower, neither of which, under the present limited production of the plants up to 1985, will be utilized to the full. There appears to be relatively little opportunity to use these investments in any sizeable degree to provide other countries with specialized apparatus and parts for nuclear power plants. There is a risk that due to rapid developments in nuclear reactor technology, part of the investments will have to be prematurely written off. The in-

[4] In the first place these are the initial costs to introduce the nuclear power system – research and development, training of personnel, storage and transportation of radioactive material, generating plants, waste disposal, testing and safety services. For the time being, a significant portion of these costs are borne by the government. Added to this are a number of uncertainties which contribute to increased costs: nuclear power plants are more likely to overrun their planned completion targets than fossil-fuelled plants; they are more prone to loss of productivity through lying idle for repairs or maintenance (thus entailing costs and losses in income).

[5] Into this category fall the larger restrictions on urban planning which nuclear power plants impose – the effects of increased thermal pollution, organization in the event of accident or disaster, the legal costs and the implications for the police force in transporting radioactive matter. Even then, this does not take into account the intangible cost factors of the influence of nuclear power systems on the health and well-being of own personnel, nor public health in general.

[6] This not only includes incidental defects cropping up in one particular plant; in many complex fields of technology (e.g. aeronautical engineering) it has occured that in the trial stages of introduction of a new technique or model, a defect was found whereby all models of a certain type had to be taken out of production and/or service until the suspect part had been checked out or replaced. If this should happen with just one section of a nuclear energy system, and supposing a significant proportion of our electricity supply were to be dependent on this, we would without warning have a serious electricity shortage on our hands. It must also be borne in mind that the nuclear power network system outside the actual plant has undergone far less testing and is more vulnerable than the plant itself.

[7] The growing discussion concerning "net energy production" of the integral nuclear power system has occasioned serious doubts as to the theory that nuclear power will contribute to reduction in oil consumption before 1985. See *Business Week*, June 8, 1974.

vestments and technological know-how are, by nature, extremely specialized and only marginally suited to application in other sectors.

Option (b), with the participation of Dutch industry, would entail attempting to take part on a small scale in a very complex and probably fast-changing field of technology, a technology which in other countries can find scope on a much broader scale and with greater governmental backing.

Furthermore, there is much more seasoned experience abroad in the field of power engineering. Option (b) therefore would not seem such a wise choice for the future of Dutch industry.

With option (c) no new type of industrial process or activity is necessitated for the construction of power plants. It is certain now that throughout the world "alternative" forms of generating energy will be implemented.

The investigation into this will require strong governmental stimulus initially, but after feasibility has been proven, the work of developing will be taken on by existing Dutch industry. With the emphasis on industrial planning, this is a very desirable situation, especially since the possibility will then open up for pursuing paths which link up with those particular fields of activity in which Holland has a leading position, viz. hydraulic engineering.

6. Obtaining Know-How and Experience

As previously mentioned, option (b) (experimental nuclear plants) brings a burden to bear initially on the National Product, whereby less leeway (funds and manpower) remains for research into other forms of providing energy. Furthermore, the available capacity resulting from option (b) will, by necessity, have to be directed to the problems surrounding nuclear energy. Investigations into other systems of providing energy will thus be seriously impaired and it is unlikely that there will be enough diverse information available in five years' time to be able to pass judgement on the various alternatives for the long run.

The argument most commonly voiced in favour of option (b) (gathering experience in the field of nuclear energy) is not valid because due to the long construction time needed for nuclear plants, it will scarcely be possible to gather even the most elementary of practical experience before 1985. For the period up to 1985 therefore, all our decisions will have to remain based upon experience gained from the existing nuclear plants: a commercial PWR, a small BWR and two experimental breeders and on information coming in from other countries.

Option (c) (no nuclear reactors for the present) provides the possibility of investing as large an amount as possible into the obtaining of information, be it on nuclear energy or on alternative sources of energy, information which in five years' time will be vitally important for long-term policy planning; at the same time the direction in which research will be carried out will hardly be restricted by a choice already made. This option is preferred in view of an orientated research policy which also will be supported by the social decision-making.

7. Physical Planning

At present work is going ahead for drawing up a coherent programme for long-term physical planning, while at the same time taking into account the more recent ideas on expedient social and economic development.

With option (c) it will be possible to take the outcome of this planning into account. The time required for planning and construction of nuclear power plants is considerably longer than for conventional power plants and this would mean that under option (b), the necessary decisions would have to be taken much earlier. Added to this, the setting up of nuclear power plants and auxiliary systems (as opposed to conventional plants) places greater limitations on the degree of freedom of future policy in the field of physical planning – the units are large, they need large quantities of cooling water, they have to be built at a considerable distance from population centres, they cannot be dismantled, the environment is again put under pressure by the manifold problems of generation, effluent disposal, the construction of heavy transmission-networks, etc.

8. Safety and the Environment

Option (c) poses no **new** safety or environmental problems. The pollutants SO_2 and NO_x from fossil fuel plants might possibly constitute a nuisance, but in point of fact they make up only a very small part of the total increase in this form of air pollution. Besides which, there are techniques known which can more than adequately keep these emissions at permissible levels, and they are economically feasible.

It is reasonable to state that in about the year 1985 industrial air pollution (with SO_2 and NO_x the major offenders) from new plants will be negligible. It is possible to forecast with reasonable certainty the upper limits of possible detrimental effects of this chemical air pollution on human life and the environment.

Option (b) (experimental implementation of nuclear power plants) carries many unknown risk hazards. It is not possible to say now what the upper limits of impairment will be. Only after a few years, when it is too late to stop, will it be possible to judge the acceptability of this choice. Particularly the risk element (imperfections in control systems and the dangers involved in storing radioactive waste) is a weighty consideration, both for man and the ecology. The risks arising from steps taken in the past cannot be neutralized, even if it were decided to completely call a halt to the nuclear energy programme.

The foregoing will also apply to the decision which must be made in five years' time, because it is likely that we will not be much the wiser on either of these above points. In this sense nuclear energy systems differ fundamentally from any other known technological system. As far as the environment is concerned, increased thermal pollution remains a disadvantage of the present type of nuclear power plants, there being no known remedy at present.

9. Public Opinion

The social introduction of a new technical system which strongly alters the structure of present society requires an adequate period in which testing of reliability on a small scale serves to promote the public's trust in and acceptance of that system. Option (c) (continuation with fossil fuel plants for the present) will meet with little opposition if the underlying objectives are made clear to all. It is to be expected that many of those people who at present actively oppose the idea of nuclear energy as a power source will be prepared to work constructively towards the implementation of a research/study programme.

The requisite experience with the system is being collected from the four existing plants and from other countries.

With option (b), it is to be expected that at each stage of im-

plementation and operation of a nuclear energy system (i.e. decision to go ahead, choice of location, choice as to type, construction, starting up, waste disposal and storage) public opposition will be met in many forms.

Not only will this cause many difficulties and delays, it will also contribute to the growth of biased opinions and extreme points of view, thus making it extremely difficult to achieve balanced public opinion in the coming five years. Nor will the plants planned for construction help contribute to public acceptance in the next 10 to 15 years because they will start up at such a late stage.

10. Freedom of Choice After Five Years

Under option (c), the whole planning policy is geared towards achieving maximum freedom of choice in five years' time, so as to be able then to arrive at the best possible long-term policy. However, five years from now, Dutch industry will be less ably equipped for nuclear technology than under option (b); but as Dutch industry will never be able to make anything more than a very limited contribution to nuclear plant construction, it will always be necessary to look abroad for the main supplies.

Under option (c), the choice of supplier abroad will be ever wider due to the absence of any so-called "obligation" towards Dutch firms, and this could be advantageous. Under option (b), there are three factors which limit the freedom of choice. First, the lack of adequate and diverse information as mentioned in section 4. Secondly, both industry and the government will have committed themselves to nuclear energy. Abandoning this commitment would involve loss of investment; during the whole period of existence of the plants, the necessary technical and social infrastructure will have to be maintained at high costs as a result of working at under-capacity.

This would give rise to a strong motivation for continuing with nuclear power plants after all. Thirdly, there remains the fact that even if the plants were to be closed down, one is still left with the problem of the radioactive waste. Supposing serious problems were to arise in the matter of radioactive waste disposal (which, at the moment, is anything but technologically "fool-proof"), for example, by faulty or ignorant grasp of essential problems during the first few years under a nuclear energy programme, then our children would be forced to suffer the consequences for many centuries to come. Even with highly perfected handling of waste, a limit to the freedom of choice would be imposed on future generations.

CONCLUSIONS

Weighing up the options in relation to the above-mentioned ten aspects, option (c) (no new nuclear plants for the moment) takes preference in all cases over option (b), the choice sometimes being very clear, sometimes less decisive. There remains no doubt that unanimous choice of (c) should form the basis for present planning. If in five years' time the investigations to be carried out will have provided us with a clearer perception of objectives, requirements and alternatives for our society, then and only then can the question of energy provision really be considered.

FISSION ENERGY AND OTHER SOURCES OF ENERGY

HANNES ALFVÉN

The problem of how to satisfy the avalanching demand for energy in the world is attracting rapidly increasing interest. The energy crisis in the United States – whether real or manipulated – has stimulated the already lively discussion. The problem has a scientific-technical aspect. What energy sources are available now and in the future, and what are the ecological consequences of their use? It has an economic aspect. What price do we have to pay for energy produced in different ways? Finally, it is associated with at least two important world policy problems, one concerning the international competition for energy sources and the other concerning the relations between atomic energy and atomic warfare. Of special importance is that the large scale deployment of fission reactors is creating an abundance of nuclear material in the world.

When the atom bombs exploded over Hiroshima and Nagasaki, many of the scientists who had taken part in the Manhattan Project became frightened by the result of their work. They tried to satisfy their conscience in two ways. Some claimed that the horror of the bomb should put an end to all wars – the same thought Alfred Nobel expressed when he invented dynamite. The Vietnam war has taught us that this was not true. Others claimed that the development of fission had given mankind the ideal source of energy – the fission reactor – which should be of such benefit that it would overshadow the curse of the bomb.

In the United States the development of the atomic energy reactor began under extremely good conditions. A competent team of scientists, trained by their work on the bomb, worked in excellent laboratories which were well financed by the U.S. government. Big industries established for bomb manufacturing switched, at least in part, to the development and manufacture of reactors, a profitable area because the U.S. government paid and took all the risks.

Development of the atomic energy reactor spread rapidly to other countries. This fast reaction was largely due however to military considerations. In some countries, namely, the Soviet Union, the United Kingdom, France and later China, atomic bombs were actually manufactured, whereas in other countries only atomic reactors for peaceful use were built. However, in several countries the motivation for building reactors was, at least initially, a desire to keep open an option for making atomic bombs sooner or later. For different reasons – technical, economical or political – no other country has yet made atomic bombs but some may "go nuclear" in the not too distant future. The strong international opinion against atomic bombs (the Non-Proliferation Treaty) and the activity of the International Atomic Energy Agency (EAEA) have been and still are a rather efficient brake on the spread of nuclear weapons.

Energy Policy Decisions

Atomic energy thus received a flying start and development proceeded. A strong motivation for further investment in nuclear reactors was that the knowledge and technology already built-up must be utilized. The result was that in many countries energy policy decisions were distorted because the primary goal was not how to cover the energy need of the country but how to find an application for atomic energy.

From what has been said, it is clear that the nuclear industry partially received its internationally powerful position due to its association with the atomic bomb. In fact, the nuclear industry has been and probably still is supported by military subventions. The enriched uranium on which the reactors in most countries depend is a by-product of atomic bomb production, and a great deal of the development work for its manufacturing has been charged to military accounts. It would be interesting to obtain an objective clarification of whether atomic energy can be considered a cheap and competitive energy source without the more or less hidden subventions.

During the period of the development of nuclear reactors some opposition to this technology appeared; but from a technical, scientific point of view these objections seemed to be unwarranted. Certainly there were some unsolved problems, but these did not appear very serious. The prospects for atomic energy looked very promising. (As a personal declaration, up to a few years ago I was convinced that fission energy was the solution to the energy problem until fusion energy was ready.)

Objections to Fission Technology

The optimistic period for fission technology ended around 1970. There were several reasons for this.

1. It became increasingly obvious that plutonium and several of the waste products, especially radioactive strontium, are perhaps the most poisonous elements we know. For example, if introduced into the human body some of them tend to be deposited in the skeleton which they irradiate for a long time, increasing the risks of cancer even if the total quantity is only a small fraction of a milligram.
2. There are in nature a number of complicated biologic processes which enrich some of the radioactive waste products by a factor of 1,000 or 100,000. It is possible that even more efficient concentrating processes exist. Therefore, it is dangerous to deposit radioactive waste anywhere in the biosphere, even if highly diluted.
3. Development of the breeder reactor was proceeding and the uranium reactors already in use began to be considered as a transition to the breeder. The breeder technology, which at least at present is mainly based on the uranium-plutonium cycle, means an enormous increase in the production of plutonium.
4. Hitherto the discussions of the waste problem referred to one or a few reactors. Now plans were made to use atomic energy to satisfy a substantial part of the world's energy needs, and that meant necessarily the mass production of radioactive waste and plutonium.
5. The waste products from one or a few reactors can be taken care of; but when a huge amount of such products is accumulated, a very serious problem appears because these products cannot be distroyed by any applicable technology. This has been demonstrated, for example, by the project to make a "nu-

clear repository" in a salt mine in the United States in Kansas, which had to be stopped because of leakage risks. Supported by competent geologists, the state of Kansas refused to accept the project.

At present there does not seem to be any existing, realistic project on how to deposit radioactive waste; but there are a multitude of optimistic speculations on how to do so. The problem is how to keep radioactive waste in storage until it decays after hundreds or thousands of years. The deposit must be absolutely reliable as the quantities of poison are tremendous. It is very difficult to satisfy these requirements for the simple reason that we have had no practical experience with such a long term project. Moreover, permanently guarded storage requires a society with unprecedented stability.

6. The ecological awakening has changed the basic view on technology. Hitherto a new technology has been allowed to take its short term advantages, leaving the long time disadvantages to posterity. The essence of the ecological debate is that such a procedure cannot be allowed any longer. Applied to our case, the fission reactor produces both energy and radioactive waste: we want to use the energy now and leave the radioactive waste for our children and grandchildren to take care of. This is against the ecological imperative: Thou shalt not leave a polluted and poisoned world to future generations.

Fission Reactors and Ecology

Because burning coal and oil with present methods produces much air pollution, it has been claimed that fission energy is much cleaner, and hence from an ecological point of view is preferable. Some ecologists, however, call fission energy "the most dirty of all energy sources."

A single reactor or a few reactors which are carefully controlled are not likely to constitute a very serious ecological threat. Research reactors, either for scientific purposes or as technical "prototypes," are rather innocent. However, if nuclear technology spreads in such a way that a considerable fraction of the energy consumption of a country or of the whole world comes from nuclear reactors, the picture changes completely. The reason is that the production of nuclear energy is necessarily associated with the production of radioactive elements; and a very large production of nuclear energy necessarily means the mass production of radioactive poisons in quantities which are terrifying.

This is the basic reason for the opposition against the use of atomic energy, which has become a worldwide controversy.

On one hand, everybody must have the deepest admiration for all the ingenious precautions the reactor constructors have made in order to contain the radioactive products and to prevent them from reaching the biosphere. On the other hand, one must also respect the objectors, who are not driven by some "nuclear hysteria" but by a very well motivated fear of a new threat to the lives and health of their generation and future generations.

With reference to some arguments which have been stated or published with regard to this controversy, it seems legitimate to state:

- It is not correct to claim that reactors are absolutely safe – because no technological product can ever be safe and no operator is absolutely reliable.
- It is not fair to claim that reactor accidents should be accepted in the same way as train and airplane accidents – because of the much more serious consequences which a reactor accident may lead to.
- It is not correct to claim that long time deposit of radioactive waste is not a serious problem – because this problem has not been solved as yet and, further, no one knows how to solve it on the required large scale if nuclear technology spreads and provides a considerable fraction of the energy consumed by a country or the world. On the other hand, one cannot exclude the possibility that future research may lead to acceptable solutions of these difficulties. There may be some chance that future discoveries may make fission energy acceptable; but we have not reached this state yet and no guarantee can be given that we will ever reach it.

Other Energy Sources

From what has been said, it seems obvious that with the present state of development fission energy should be accepted as a large scale energy source only if the need of energy is desperate and no other sources of energy exist.

How much energy *really* is needed in an acceptable society will not be discussed here. It is obvious that technological civilization is on its way to a limitation. We have reached a new stage in the development where our actions can no longer be dictated by a desire to increase the population or the consumption of a country. We shall confine ourselves here to the technical-scientific problem of how to solve the energy problem.

When comparing different sources of energy we must observe that a large amount of competent work and much money have been invested in fission energy, whereas very modest efforts have been made to develop other forms of energy. As stated above, the reason for this is because in many countries the problem has not been how to solve the energy problem, but how to give fission energy not only military but also civilian use. Accordingly, we must start thinking in a radically new way: *We must imagine how other sources of energy would have appeared today if research and development had been concentrated on them.* And what we could have expected of them in the future.

Apart from fission energy, the following energy sources are discussed as serious alternatives:*

Fossil fuels. It is often claimed that oil and natural gas sources will suffice only for the next 20 years; but in view of the fact that large new sources have been discovered, they may last much longer. In any case, there is coal sufficient for centuries. At present the environmental objections to fossil fuels are serious. However, one may hope that if research of the same quality and quantity that has been devoted to fission energy is directed to a non-polluting handling of fossil fuels, these sources may supply the world with energy for a long time and in a way that is tolerable for the environment. There are several new ideas of how to utilize the huge coal reserves in a clean way.

Fusion energy. A decisive difference between fission and fusion energy is that the fusion processes of interest result in non-radioactive end products. However, the intense neutron flux from a fusion reactor necessarily produces some radioactivity in the structure of the reactor. Also, a fusion reactor contains tritium, as an intermediate product which is radioactive, and this causes some leakage risk. There is no doubt that from an ecological point of

* Hydropower and wind and tidal energy are not considered here; hydropower is geographically limited, and wind and tidal energy do not seem to be available in large quantities as to be of importance except in special cases.

view the fusion reactor is much less objectionable than the fission reactor. It is often claimed that technical fusion reactors will not be developed before year 2000 and, therefore, fusion energy should not be mentioned in the present debate. The causality chain may be the reverse: as the breeder reactor lobby does not like the competition with the fusion alternative, this is eliminated by the claim that it belongs to a very distant future.

Solar energy. As each square kilometer of the Earth's surface receives as much energy from the Sun as a big fission reactor delivers (about one GW), we have here an inexhaustible and completely clean source of energy. It is, however, at present very expensive. New research results give reasons for optimism about the future economy of solar energy.

Geothermal energy. Geothermal energy means energy from the hot interior of the Earth. Outstreaming vapor and hot water in volcanic areas have long been used, for example, in Iceland, Italy and the Soviet Union. A new method, called the "hot rocks" method, has been suggested recently. Two holes close to each other are drilled until a hot region is reached, perhaps about 5 kilometers downward. The rock between the holes is cracked by some method. There, water is poured down through one of the holes, and when it comes in contact with the hot rock it is vaporized and comes up through the other hole as steam. This may constitute an almost inexhaustible source of energy for all countries, especially for those countries in which the rocks have a high thermal gradient.

The Human Factor

Fusion, solar and geothermal energy sources are not yet sufficiently developed to ensure the solution of our energy problem; nor can we be sure that fossil fuels can be handled in a clean way as to satisfy the environmentalists. But, as both the Manhattan project and the Apollo program have shown, our science and technology are so powerful that if an intense effort is made, we can do almost anything we want in, say, 10 years – provided we are not in conflict with the laws of Nature!

It is obvious that the present international debate is creating new ideas; and it is very likely that energy sources will be found which may make fission energy unnecessary. It is, therefore, a mistake to concentrate energy policy on a line which initially seems attractive, but which in the near future may be considered obsolete and dangerous. As we have learned from history, it is a normal process that a technology which at a certain time seemed attractive is substituted with a better one at a later time.

As stated above, we cannot rule out that new discoveries will make fission technology acceptable by solving the safety and the waste disposal problems. However, as so much highly qualified work has already been devoted to these fields, this is not very likely. We now recognize that these problems are not the usual scientific-technological problems but are ones closely connected with the "human factor". To what extent can we trust that operators will really do what they are instructed to do? Do the social systems in different countries and in the whole world possess the unprecedented stability which the fission technology requires? This means that the basic questions fall outside the field of competence of the fission technologists.

Inseparable Twins?

Are the military and the peaceful atomic energy programs inseparable twins? Another strong objection to fission energy is derived from its close relation to atomic bombs. This relation is clarified in a number of reports of the IAEA and in the Stockholm International Peace Research Institute's *Yearbooks* as well as at a June 1973 SIPRI symposium on "Review of Nuclear Proliferation Problems". There is no doubt that the IAEA has had remarkable success in constructing a system of international inspection of nuclear material, according to the plans of the Non-Proliferation Treaty. However, not all countries have signed the NPT, and even for those countries which have signed it, IAEA authority is confined to inspection. There is no guarantee that efficient international sanctions would be applied to a country which breaks the Non-Proliferation Treaty.

According to existing plans, within 10 years the production of fissile material for peaceful purposes will be sufficient for the production of about 10,000 atomic bombs a year.

It has been claimed that the large plutonium quantities produced by the reactors cannot easily be used for manufacturing bombs because of the difference between "reactor plutonium", which is normally produced in the reactors, and "weapon-grade plutonium", which is used for atomic bombs. The former is obtained when a reactor is run in the economically most favorable way, with change of fuel elements about once every 18 months; the latter is obtained if the burn-out is limited to a few months. However, there is no serious technical difficulty for an establishment possessing complete fission energy equipment, to change to the production of weapon-grade plutonium. Moreover, even ordinary reactor plutonium can be used for making bombs, certainly somewhat clumsy and with less than maximum yield and less accuracy of performance, but anyhow terrible enough. Hence by stealing some 20 kilograms of ordinary reactor plutonium, a guerrilla or a criminal could obtain possession of the material for making atomic bombs.

It has also been claimed that the technology of manufacturing bombs is a very difficult process and requires knowledge of "atomic secrets". Today this is not true. Certainly, fabrication is not so easy that anyone could make an atomic bomb "in his garage" after having stolen a sufficient quantity of plutonium, as is said sometimes. But, according to what appear to be reliable reports, only a few engineers with a normal scientific and technical education and a good but not very fancy workshop are needed to make a bomb. This conclusion is quite reasonable from the point of view of the general experience of the technological development. What was a top scientific-technical achievement in 1945, when the first atomic bomb was made, may very well be an achievement that is rather easy to repeat in 1974. (However, the hydrogen bomb is still difficult to make!)

With all this in mind it is difficult to imagine how a proliferation of atomic bombs can be avoided in the future – when according to existing plans thousands or tens of thousands of atomic reactors will be working all over the world, and when the enormous production of plutonium from breeders has started. Indeed, it will be extremely difficult to prevent atomic bombs from falling into the hands of many groups of people who may like to use them for political or criminal purposes.

If we want to promote the spread of nuclear technology, the only way to avoid such a proliferation of nuclear bombs seems to be to impose very strict police control over the whole world. (Compare, Alvin Weinberg, "Social Institutions and Nuclear Energy". This will be difficult to achieve and does not lead us to a very attractive future society.

IN SEARCH OF TECHNOLOGICAL SELF-RELIANCE:

TWENTY-FIVE YEARS OF NUCLEAR ENERGY IN INDIA

RAJ RAMANNA

In understanding the rapid development of the utilization of nuclear energy in India, it is useful to recall the organization of science as it existed in India before independence. Pre-war scientific developments in India were concentrated, not unexpectedly, in universities. The biggest impact of science came from the Calcutta University and owes its origin to its great Vice-Chancellor Sir Asutosh Mukherjee. Because of his inspiring organizational genius the country can boast of Raman, Saha and others. However, the structure and organization of those times encouraged the development of individual scientists. Research on a wider scale involving industry and team work just did not exist and, we may surmise, was neither encouraged nor looked upon with favour. There was however one exception, the Indian Institute of Science at Bangalore. But even here the time was not ripe for large scale technological research. It is, however, good to recall that it was in this Institute that the founder of the Atomic Energy Programme in India, Dr. H.J. Bhabha did much of his early thinking leading to a new science structure for the country.

That the organization of research in universities existing during the pre-World-War-II period was insufficient was realized by a group of scientists working during the war. Amongst these were Dr. H.J. Bhabha and Dr. S.S. Bhatnagar. During these years Dr. Bhatnagar dreamed of a chain of national laboratories in various disciplines all over India. At about the same time, Dr. Bhabha was planning a centre of excellence in nuclear science in Bombay. He was already aware of the possibilities of the energy contained in the atom and expressed it in his now famous letter to the then Chairman of Sir Dorabji Tata Trust in 1944 in connection with the establishment of the Tata Institute of Fundamental Research:

> *When nuclear energy has been successfully applied for power production, in say, a couple of decades from now, India will not have to look abroad for its experts, but will find them ready at hand.*

Real developments in nuclear science can be said to have started with the foundation of the Tata Institute of Fundamental Research (TIFR) with funds provided by the Trustees of Sir Dorabji Tata Trust and later by the Government of Maharashtra (then Govt. of Bombay). The Central Government now provides nearly 99% of its recurring budget. This institute started off in a small wing in a flat in Peddar Road, mainly to provide the necessary facilities for Bhabha's own work in cosmic rays and theoretical physics. But with the coming of independence, he clearly saw that the TIFR could provide the base for a nuclear energy programme and he would have to expand the facilities of the Institute to include other branches of physics, and disciplines such as chemistry, biology and engineering. At his instance and with the help of S.S. Bhatnagar, the Atomic Energy Commission was formed in August 1948 with the following charter:

(1) To take such steps as may be necessary from time to time to protect the interests of the country in connection with atomic energy by exercise of the powers conferred on the Government of India by the provisions of the Atomic Energy Act;

(2) To survey the territories of the Indian Dominion for the location of useful minerals in connection with atomic energy; and

(3) To promote research in their own laboratories and to subsidize such research in existing institutions and universities. Special steps will be taken to increase teaching and research facilities in nuclear physics in the Indian universities.

As can be seen in the charter, priority was given to the survey of natural resources, particularly materials of interest to an atomic energy programme such as uranium, thorium, beryllium, graphite, etc. A special unit with the original name of Rare Minerals Division was created at Delhi with the help of the late Prof. Wadia. The next priority was given to the basic sciences, particularly physics, chemistry and biology with the purpose of providing facilities to and training up high quality research scientists. The eventual aim was to set up as early as possible a research reactor. It was realized that this by itself would not be sufficient for a nuclear programme unless there was simultaneously a programme for instrumentation, particularly in electronics. Dr. Bhabha realized very early in the programme that no high quality research is possible without good instruments and the very act of their being produced in India would itself be progress. For this purpose a unit called the Electronics Production Unit was started in the TIFR. This production unit formed the nucleus of the large corporation now in Hyderabad known as the Electronics Corporation of India Limited.

Considering the number of people who have been recruited directly from various training centres abroad and some very enthusiastic good students from Indian universities themselves, it is not easy to explain what it is that made all the people at that time work in close teams and discuss their problems with one another with absolute freedom. This was certainly different from the atmosphere that existed in other institutions and universities where the tendency was to work in separate compartments. It is possible that this was because of Dr. Bhabha's quick perception and understanding of various disciplines and by his talking to people in different sections at all levels. He used to make a knowledgeable assessment and appreciation of each man's work and was able to bring in a truly cooperative spirit. It was in this way that a deep foundation was laid for multi-disciplinary cooperative work even as early as the 1950's. The spirit and tempo of research was maintained by inviting many distinguished scientists from abroad as well as from India, and the Wednesday colloquia at TIFR were often great intellectual events. The names of Dirac, Pauli, Bohr come to my mind.

While this foundation was being laid for a strong base in pure science and some work in electronics instrumentation there was

a clamour in the scientific circles all over the country as to whether this was indeed leading to one of the aims of the Commission of setting up a small reactor. I recall Dr. S.S. Bhatnagar bemoaning to Dr. Bhabha in London in 1953; his words were "will I ever see a reactor in India before I die". Unfortunately our first reactor came into operation in 1956 only after the death of Dr. Bhatnagar (1955).

In order to have a countrywide discussion on our atomic energy programme, particularly on the choice of a reactor, its siting and the difficulties of setting up one indigenously, Pandit Nehru called a conference to which distinguished Indian scientists were invited. This was held in Delhi during the winter of 1954 at the National Physical Laboratory. We, who were heading various Divisions, were also asked to speak on our speciality. At this conference, I recall the presence of Prof. M.N. Saha, Prof. S.N. Bose, Dr. K.S. Krishnan and several other distinguished physicists, chemists, engineers and industrialists from all parts of India. On that day, one could feel the tension in the air. The location of the Atomic Energy Establishment at Bombay was being questioned. The choice of the reactor type and the entire programme of developing our atomic energy materials came under criticism. Pandit Nehru carefully listened to all the arguments, particularly to the various proposals on the type of reactor we should try and build by ourselves. With all our youthful enthusiasm we must have made an impression. Certainly Dr. Bhabha had the entire discussion under control, but it was Prof. K.S. Krishnan, the last speaker, who clinched the argument in his usual humorous style by quoting the story of Jakobi and his student. I quote it because the story made a big impression that day:

> *Yesterday, I mentioned the instance of a man, a young man, who had joined for research the great mathematician Jacobi who was the brother of the great orientalist. The young man had been with him for several months without having started any research work. When the teacher asked him about it he said 'I have not yet read all the earlier literature on the subject.' Then the Professor turned to him and said, 'Dear man, if your father had waited to see all the girls before marrying one, where would you be? I would like you to make a start somewhere. Get on with the scientific problems and proceed'...*

This conference was one of the most important ones on atomic energy held in India; it consolidated scientific opinion in the country in support of the steps taken by Dr. Bhabha towards the fulfilment of our programme.It was also clear that Pandit Nehru had given his full support to the programme publicly in front of all the scientists, some of whom had been very critical.

Due to Dr. Bhabha's close contacts with European scientists and his influence among the leaders of science in Europe, he was in constant touch with technological developments and possibilities abroad. He had managed to have an agreement of cooperation with France long before such agreements existed in this particular field outside the then nuclear countries. It was with the cooperation of France that we learnt a lot about reactor materials, reactor control, neutron physics etc. particularly with respect to natural uranium systems. But all this still had not put us in a position to build a reactor of our own. However, sometime in 1954, after one of his fairly frequent tours of Europe, Dr. Bhabha came back with a proposition that Sir John Cockroft had offered some enriched uranium fuel elements for building up a Swimming Pool type reactor and that he had come to an agreement with him for the loan of this fuel. It was however to be a challenge in that we had to build the rest of the reactor which included the civil engineering, design of the tank, and electronics control systems and prepare for its utilization entirely by ourselves. There was a built-in competition with the Lido reactor at Harwell as to who would complete theirs first. (I may add that we went critical earlier by a few days.) Since the whole project was a challenge, everybody seemed keyed up and it was one of those operations which was carried out with tremendous gusto. The reactor building was constructed in less than a year's time and because of this hurry it turned out that neither the roof nor the walls were leak proof against the monsoon. The Swimming Pool tank was also built in a record time, and by August 1956 the reactor was actually ready for criticality trials; the whole operation having lasted just one year. At the first trials in which Dr. Bhabha himself took part, it became difficult to try out various configurations of the uranium fuel in the water because the tank was still new and the water was not sufficiently transparent. Though we worked during the whole of the second night, the reactor just would not go critical. This was because we had left a very big water gap in the centre not knowing enough about such neutron multiplying systems. This was realized on the 3rd day, the whole loading operation was reenacted on the 4th day, and on that 4th afternoon the reactor went critical. We could now claim that we had a critical reactor, the first in Asia, built entirely by ourselves except for the enriched uranium fuel. I also recall that within a few minutes after the reactor became critical, the Prime Minister, Pandit Jawaharlal Nehru was informed of it over the phone, even as the monsoon was flooding the whole place around us.

I have dealt in some detail about the Apsara criticality because it had such a large psychological impact on the country for the development of modern technology. Though a lot of equipment for the reactor had been designed and made entirely by us, there were still many people not willing to believe that we could establish such modern technology in the country by our own efforts. The country seemed to be covered in a cloak of non-self-reliance. People in general felt that everything had to be imported from abroad, be it ideas or equipment. It seemed to many in India that nothing worthwhile was possible by ourselves.

We realized that to cash in on the success of Apsara we had to take a series of steps to make ourselves self-sufficient not only in quality but also in quantity. Even before Apsara went into operation, the Indian Rare Earths Ltd. was producing uranium and thorium compounds of high purity. A decision was taken to build a Uranium Metal Plant immediately, and this turned out to be vital in our programme of self-sufficiency.

At the Geneva Conference in 1955, Dr. Bhabha played a very important role in bringing about a discussion both of the importance of nuclear power for developing countries and of the possibilities of fusion. It was during this conference that a very generous offer from Canada was made to us of the gift under the Colombo Plan of a NRX type reactor, a natural uranium and heavy water system.

I recall the very heated discussion which Dr. Bhabha had with all of us in Geneva in 1955 on the choice of the NRX type reactor for Trombay. While all of us including Dr. H.N. Sethna, Shri N.B. Prasad, Shri A.S. Rao and myself were keen on the NRX type reactor because it was a natural uranium-heavy water system and therefore a type which in principle we could fuel ourselves, for some reasons, Dr. Bhabha seemed to favour the Dido reactor, an enriched uranium heavy water system, a type which was in operation at Harwell. He must have been slightly influenced by the views of Sir John Cockroft. As a concession, he said we should have both types of reactors, but we all impressed upon him

that we were not sufficiently advanced in manpower and other industrial facilities to have two high flux research reactors going. Discussions were heated and finally Dr. Bhabha gave in to our views and rightly so. I refer to these discussions to show how decisions were taken between himself and his younger colleagues and how Dr. Bhabha was willing to accept suggestions in spite of his own tremendous personal reputation.

With the starting of construction of the NRX reactor, a decision seems to have been taken (in which I was not involved) for setting up a Reprocessing Plant to process the plutonium produced in the Cirus reactor. Prior to this, a decision had already been taken to produce the fuel necessary for even half of the first charge of the Cirus reactor. At this time, Canadians were insisting on some sort of safeguards for the fuel that they were going to supply to us for this reactor. When it was pointed out that we could probably make the fuel elements ourselves, they wrote warning us that this was a very difficult metallurgical operation which had taken them considerable effort; but we were welcome to try and produce it but could always come to them in case we failed. From the tone of the letter, it was clear that they did not expect us to make fuel elements of the required quality and that we would eventually go to them for buying the fuel. Later, as it turned out, the fuel elements produced at Trombay were even better than the Canadian fuel elements. This event must be the first example in which our own technology established itself as being equal to that in the front rank of world technological developments. Our contributions to basic sciences have always been appreciated in knowledgeable circles over many decades, but this was certainly the first sophisticated technology developed independently of foreign help. Our metallurgy and radio-metallurgy laboratories must now be among the best in the world.

No record of the developments of atomic energy in India will be complete without some references to the problems we had in getting the Cirus reactor critical. A few days prior to the dedication ceremony, difficulties occurred with the reactor: for unknown reasons the cooling channel of the fuel tended to become choked. This, as we discovered later, was due to bacteria developing because of local conditions in the water at our ambient temperatures. At that time, the Canadians were unable to identify the cause of the trouble and they left the reactor to us to set right. The cause was identified by our biologists and chemists, and suitable remedies were undertaken so that the reactor could function at its rated capacity of 40 MW. Since then, except for some minor problems for a very short period, the reactor has worked in an exceedingly satisfactory way. I must, of course, give due credit to the original designers of this type of reactor, the NRX, including many scientists of international repute such as Sir John Cockroft and W. Bennett Lewis.

The setting up of the Reprocessing Plant at the same time when Cirus became critical caused some eyebrows to be raised; clearly it gave India a nuclear option. At the opening ceremony of the Reprocessing Plant, Shri Lab Bahadur Shastri offered this plant to countries of South East Asia for reprocessing their fuel in case this was required. However, this has not been utilized by any of the countries. It was, however, made clear that the plutonium reprocessed in this plant, would be used for building future types of reactors, particularly fast reactors. The fast breeder reactor using plutonium is now a very important part of our programme.

It was becoming clear to us that in our power programme we would be leaning on natural uranium heavy water systems, particularly as a result of Canadian experience and their generous offer to share the know-how with us. The Cirus reactor was followed by the Zerlina reactor (1961), which was designed to obtain physics information on such type of reactors. It was built entirely by ourselves.

Whereas the programme of research reactors and its utilization forged ahead, decisions were taken to develop all aspects of atomic energy for peaceful purposes. In fact the atomic energy programme in India at that time was designed to act as a spring board for modernizing its scientific effort. A large programme of isotope preparation, sophisticated laboratories for studies in transuranium chemistry, highly specialized laboratories for physics, particularly neutron physics, various aspects of solid state physics, solid state chemistry, and preparation of pure materials were established. An intensive programme of biological research including genetics, mutation research, agriculture and medical research was also initiated in a very large way. This is by no means a complete list.

During the years 1955-60, while the Apsara reactor was set up and other important facilities were in the process of construction, it can be said that they constituted the "meat" required for setting up of an organization. It was also during this period that the real foundations for a proper base in science was established in the country by a proper reorganization of the administration to make it more responsive to scientific research and the establishment of training programmes to provide for the necessary specified manpower.

Since the inception of TIFR, it was clear to us that the training offered by our universities was totally inadequate for an atomic energy programme. Though we had managed to get very good people from the universities, with the growing size and number of universities, it was becoming more and more difficult to locate good people. For this purpose a Training School programme was started in 1957. This training programme has paid its dividends many times over. It has provided the base for all our projects and many trainees from this school hold important positions. The Training School provides not only a place for training and orienting bright people towards atomic research, but also gives them the necessary atmosphere to develop a sense of loyalty and team work. It also provided a body of brilliant young men who question their senior colleagues, and has thus provided an intellectual background to help aging scientists remain youthful. While the Training School was one of the most important efforts in utilizing our manpower, other training programmes including training in Canada for the Cirus reactor and later the power reactors provided the Indian atomic energy programme with the manpower base without which the rapid development would never have been achieved.

Dr. Bhabha used to say that we could justify to the public at large all the expenditure on atomic energy that was being incurred only if we could demonstrate useful electric power generated at low cost. Right from very early days of atomic energy, he had set himself the task of costing nuclear power specially in developing countries. His contributions to the Geneva Conference of 1955 show his absorbing interest in the need for and cost of nuclear power in developing areas.

He had to fight a long battle because his European colleagues were against him on this matter. When it became clear that light water enriched system of the BWR type was already economical in comparison with thermal stations under certain circumstances of distance from coal fields, Dr. Bhabha involved himself in a series of negotiations with the US Atomic Energy Commission for the establishment of the Tarapur reactor. The reactor actually

started giving power to the Maharashtra and Gujarat grids after his death. Whatever difficulties the Tarapur reactor has been faced with, which in my view are very exaggerated because the reactor has behaved no better or no worse than other nuclear power stations in the world, it has provided a source of very important power for the Maharashtra-Gujarat grid, invaluable for the industry in the two states. The recent decision to make fuel elements for this reactor from imported enriched uranium (in UF_6 form) is a courageous decision taken in the same spirit as the decisions of Dr. Bhabha.

Our close association with Canada led us to the choice of heavy water natural uranium power reactors (Candu type). In this choice, I think we can consider ourselves to be lucky as it has led us to the right system and unit size required for the country under the present conditions of our industry. The Site Selection Committee for the location of nuclear power reactors, which was formed in August 1961, made a series of recommendations, as a result of which Kota and Kalpakkam were chosen as locations for the first two power stations. It was clear even at that time that while Kota would be built under Canadian assistance, Kalpakkam would be built almost entirely from Indian resources. The unit size of 200 MW was naturally dictated from the first Canadian power station at Douglas point. It has now been shown that the unit size of 500 or 1000 MW would make the electricity much cheaper to the extent that it will be competitive with thermal power even at coal pit-heads. If however, we have in mind the size of the present grid systems and the capability of our industry, 200 MW would still be of value for some years to come. 500 MW stations are in fact being designed by us, but should really come into operation after the Narora reactors.

It has always been the aim of the Indian atomic energy programme to utilize the large quantities of thorium that exist in the country. Unfortunately, thorium cannot be used as a fuel as it will have to be irradiated in a reactor to produce sufficient quantities of U^{233} which can then be used as a fuel. The production of U^{233} in normal reactors is a very slow process. However, nuclear physics provides a most exciting answer to this in the sense that it is possible to build reactors using a fast neutron spectrum in which more fuel can be produced than is actually burnt. Such reactors are called breeder reactors. If thorium is used as a blanket around the core of these reactors, large quantities of U^{233} can be produced. There are, however, many problems connected with this type of reactor including the economics of breeding. The other problems referred to are reactor stability, reactor safety and radiation damage. Reactor safety in fast breeder systems is particularly important in view of the fact that sodium is used as the coolant for extracting the power inside the reactor. I would say that in the plans of Dr. Bhabha's programme, the fast breeder reactor was the last big item he had envisaged. A fast breeder test reactor is now under construction at Kalpakkam and is just coming out of the ground. It should be operating by 1977-78 and by the early 80's we will have obtained considerable operating experience on such systems, to be able to design a power breeder reactor to come up in the late 80's. A power breeder reactor will go a long way to help conserve our fuel supplies for nuclear power, since it produces more fuel than it burns. If the experiment succeeds it will have a big impact on fuel economics.

I have in this brief sketch of developments of atomic energy not mentioned several other developments which have gone a long way towards making the Indian nuclear programme a self-sufficient one. The chain of heavy water plants which has been set up all over the country will make us independent of imports of heavy water. The Uranium Corporation of India set up in October 67 is responsible for all the mining and processing of the available uranium ore in the country. The very large Nuclear Fuel Complex at Hyderabad which has been set up entirely by our own scientists and engineers is something the country can be proud of. It makes several types of sophisticated fuel elements for our power and research reactors and also produces materials of high purity of immense value to our industry, e.g. zirconium, titanium etc. If in fact, I am asked to point out a large establishment, next to BARC, which had led us to a high degree of self-sufficiency in an atomic power programme, I would mention the Nuclear Fuel Complex. An atomic energy programme is incomplete without waste handling facilities. This is essentially because atomic reactors produce hazardous radioactive wastes which have to be treated and stored very carefully, in order to avoid any hazards to the environment. Practically at every power plant, we have a large waste disposal unit to take care of the hazards aspects of atomic energy programme. I have a feeling that several countries believe that we are somewhat over-cautious in our health physics and protection programmes, but in the particular case of atomic energy, I think it is better to be on the safe side.

As a measure of our self-sufficiency in very sophisticated technology, I would like to mention the completely indigenously fabricated atom-smashing machine called the 60 Mev Variable Energy Cyclotron being set up at Calcutta. This has a curious history. For several years, the nuclear scientists had been asking Dr. Bhabha for his encouragement and support in building a big cyclotron to provide the necessary facilities for the large number of nuclear physicists available in the country. For some reasons, he had been very hesitant about this programme. He, however, set up a committee to report on the various types of cyclotrons in existence and their possible uses. A report was prepared and the same time a conference of all nuclear scientists was called at Bombay in August 1964 to take a decision on the programme. After hearing the case presented by the scientists, Dr. Bhabha became favourable to such a facility. As a result, a very sophisticated variable energy cyclotron with practically all the components made in India either at Trombay or in the public sector like Bhopal and Heavy Electricals, Ranchi is reaching a stage of completion at the SALT Lake site at Calcutta. The machine is expected to go into operation sometime early in 1975. Though this cyclotron was originally planned to be a nuclear physics facility, it has now become clear to all of us that it will be one of the most important tools for the study of radiation damage in solids of special value in a fast reactor programme. When we were in process of trying to convince Dr. Bhabha of the usefulness of this machine and had almost succeeded in doing so, for some unknown reasons foreign scientists used to write to him dissuading him from giving any encouragement for this project. I have never understood this negative interference from outside scientists for a programme which we now know will be of immense value to physics and our pure research programme. The most inexplicable part being why these foreign scientists at the same time were permitting their own scientists to build a facility in their own country.

The first phase of our atomic energy programme lasted from 1948 to 1956 when the Apsara went critical; the second phase of planning and construction of large facilities lasted from 1956 to 1966 when Dr. Bhabha died. 1966 to 1974 represents the phase of construction of power stations and utilization of large research facilities. I have briefly described the developments in atomic energy in the last 25 years taking us to the year 1973. There has been recently added interest in our atomic energy programme since we

carried out a peaceful nuclear explosion on May 18, 1974 in the deserts of Rajasthan. I do not have to say that this is an experiment in which the design, planning and execution are all done with Indian resources and by our own scientists. I am pretty certain that had Dr. Bhabha been alive, he would have strongly supported the aims of our experiments on the 18th May and I can say from my long personal association with him that he was keen on understanding all aspects of peaceful uses of atomic energy including nuclear explosions. We have shown that at low cost one can carry out a peaceful nuclear explosion which is fully contained. We have described elsewhere its possible uses but we still have to study carefully the behaviour of radioactive substances underground. The drilling for obtaining such information is in full swing.

These great achievements of Dr. Bhabha and his colleagues in the last 25 years would have been impossible but for the firm support and encouragement given by the late P.M. Pandit Jawaharlal Nehru who died about 10 years ago. His faith in science was immense and I hope the scientists in the Atomic Energy Commission have been worthy of his confidence. I am happy to say we have received the same support from the present Prime Minister and her genius for clear and well defined decisions have already helped us to make our contributions to the development of the country in the atomic field. While progress in atomic energy has reached peaks, I see it as an important prop to the whole of our industrial development and structure.

ASSESSING INDIA'S NUCLEAR EXPLOSION

The explosion of a nuclear device by India in the deserts of Rajasthan on May 18, 1974 stirred up a world-wide public debate and drew attention to the development of the atomic energy programme in India. The following two reactions by Indian Christians offer different perspectives. The first is an excerpt from a response by the Indian YWCA to a letter from the Canadian YWCA which expressed concern about the proliferation of nuclear weapons and nuclear testing for military purposes by any country and supported the Canadian government's protest against the nuclear explosion by India. The second comment is an editorial note from the Indian weekly "The Guardian", written a few days after the nuclear explosion and assessing its political implications.

A GREAT STEP FORWARD

YWCA OF INDIA

To all the insistently voiced doubts regarding the motivation behind India's nuclear experiment, the answer is: the nuclear implosion is a tremendous step forward in the continuing process of acquiring technological knowledge essential for the development of indigenous resources in the future. No country with a population of the size of India can affort to put itself permanently in a position of dependence on foreign technology and know-how. It must not only seek to come abreast of other nations but also to innovate and discover new ways of solving its formidable problems. Technology is man's principal aid in achieving supremacy over environment. India aims to use nuclear technology precisely in this manner. Scientists have all along drawn attention to alternative uses of this awesome source of energy. India now intends to explore these for the benefit of its own people. Canada's complaint that its aid has been misused is not valid. There is nothing to suggest that the explosion had a non-peaceful purpose, and, although at least part of the plutonium was presumably extracted from the used fuel of the research reactor at Trombay built with Canadian assistance, the fuel in question was not supplied by Canada, but produced in India.

One of the most widely levelled criticisms against India's nuclear experiment has been that it distorts priorities. This criticism is obviously based on the assumption that nuclear research is extremely costly, and something which a poor nation can only afford by some perverse ordering of its priorities. India has now explained, in many forums, that the cost of the Indian experiment was low enough to have been well within the limits which any country in India's position can legitimately incur on research and development.

Another frequently asked question is whether nuclear technology is the kind of technology India should invest in. To start with, what technology a country chooses to develop is best determined by that country itself. Secondly, there must be a strong presumption that if a country is capable of achieving success in a highly complicated area of science and technology it ought to be capable of taking decisions with respect to alternative technologies which are in its best interest. Thirdly, research in technology is an investment in time, and surely if any country needs such an investment, India with its 600 million population does.

* * *

A number of peaceful uses for nuclear technology are already known. These have been catalogued often enough, but what has rarely been done is to focus attention on the fact that nuclear experimentation has so far been essentially geared to the development of nuclear weaponry and scientific data for other purposes have not been assembled methodically or made use of systematically. In any case, such data as might exist are not available to developing countries. This lacuna needs to be filled. The nature of the Indian experiment clearly shows that it aims to do this. The emphasis was mainly on collecting geological and related data as a consequence of the blast and these data are now under intensive examination. It is a known fact that nuclear explosions can be used for releasing oil and gas from deep wells, forming artificial lakes for irrigation, and putting out giant fires in gas wells.

It is not surprising that most developing countries have welcomed the Indian experiment. For them it opens a door – a door that might reveal new possibilities for development. It is good news for them that the farthest reaches of technological advances would now be available for promoting human welfare in their countries.

India has asserted herself against the Nuclear Non-Proliferation Treaty because as it stands, it is a discriminatory one. As long as it is possible for some countries to develop their nuclear power, there must always be freedom for others to do so. Further, till a total ban on specific channels of implementation are arrived at and incorporated at the world level, there must always be freedom for development.

A POLITICAL DECISION

NINAN KOSHY

The breakthrough achieved in nuclear technology by India is commendable and our scientists deserve warm praise and congratulations for this remarkable achievement. Solid foundation for this significant advance in sophisticated technology was laid by the late Dr. Bhabha and Jawaharlal Nehru and gave considerable encouragement to our atomic scientists. We are already using nuclear energy for power purposes from two atomic plants and we are now told that the peaceful nuclear explosion experiment using plutonium and the fission technique was carried out to study rock dynamics and how nuclear explosion could be employed for construction of dams and canals and for stimulation of gas and oil. The test appears to have created a new sense of confidence in the technological and political leadership of the country and judging from the press reports there is widespread enthusiasm about the achievement. The psychological fallout is remarkable.

Reaction from the different countries of the world has been on predictable lines. There is sharp criticism from the Western countries except France; general appreciation among East European countries; a mixed reaction of appreciation and confusion from Afro-Asian countries (though a few have openly lauded India's achievement); virulent political propaganda against India by Pakistan; consternation and regret at the United Nations. The Indian Prime Minister was right when she said that the rich Western nations had no right to criticise India for demonstrating her nuclear capability. The United States especially can be accused of being the most guilty nation in the world as far as nuclear proliferation is concerned. The Non-Proliferation Treaty which became effective from March 1970 arbitrarily divided the world into two mutually exclusive categories, nuclear weapon States and non-nuclear weapon States. Members of the nuclear club, especially the United States, seem to be worried about the status of India and the effect on the Treaty, if India now expresses its desire to sign the Treaty. As Senator Edward Kennedy stated: "The real failure to prevent the spread of nuclear weapons rests not with India but with the United States, Soviet Union, France, China and Britain and more especially on the United States and Soviet Union for their failure to conclude a comprehensive test ban treaty." The Non-Proliferation Treaty is one of the most unequal international treaties ever signed because while it prohibited the nuclear have-nots from acquiring nuclear capability it left the haves free to add to their arsenals. At that time India had demanded a commitment from the nuclear powers not to use nuclear weapons against those who did not have them, a comprehensive test ban treaty, a complete freeze in the production of both nuclear weapons and delivery systems and a substantial cut in the nuclear weapon stockpile of the nuclear powers. India's spokesmen have emphatically and repeatedly asserted that India's nuclear capability will be utilized only for peaceful purposes, and the explosion has been called 'peaceful nuclear explosion'. But our leaders are not so naive as to ignore the political impact of the explosion domestically and internationally. In fact there are those who argue that the explosion was timed to give a political boost to Mrs. Gandhi, during a period of widespread frustration. Even if attributing such motives is not justified, there are a few questions and issues which need discussion. The simple fact remains that there is no distinguishing factor between a nuclear test for peaceful purposes and a nuclear weapon test, and therefore the test has placed in the hands of India options which are open. It is not therefore surprising that India's declarations are not convincing to many nations. Even in the exploration of peaceful uses of nuclear energy, was the explosion a justifiable priority? Do we have today more potentialities for peaceful uses of atomic energy than, say, Canada or Japan? Explanations given by official spokesmen are not very satisfactory in this respect.

The Institute of Strategic Studies, London, in one of its studies as early as 1962 had concluded that India was capable of exploding a nuclear device in 1963. When China exploded its first atomic bomb on October 16, 1964 many asked the Government why India should lag behind in production of nuclear bombs. Dr. Bhabha at that time announced that if India wanted the bomb, it could manufacture it in 18 months, making it abundantly clear that already India was capable of exploding a nuclear device. If such an explosion was a priority test for peaceful purposes why was it delayed for ten years? Was it because of the pressure of the super-powers? It has been reported that the Cabinet clearance for exploding a nuclear device was given in 1971. Did this have anything to do with the war with Pakistan and the tilt of the US towards Pakistan? It is because questions like these remain that the political implications of the achievement have to be taken seriously. It has to be noted that the test has already strengthened the pro-bomb lobby in the country.

The reaction in Pakistan especially is thus predictable. Of course it can be stated that Mr. Bhutto in his characteristic manner would make use of this for a 'crusade' to suit his domestic and foreign political ends. He has in fact already started the crusade. But what about the ordinary Pakistanis? It has to be conceded that our peaceful explosion has caused much anxiety there. To them the realization that a country with which they had to fight three major wars is a nuclear power is not a pleasant one. This has of course nothing to do with the fact that even if India wants, as the world is constituted today, India will never be able to use nuclear weapons against Pakistan. But there is no use denying the fact that our new achievement has added a new dimension to the tension in the sub-continent and knowing the Pakistani psychology it is likely to retard the progress towards normalisation of relations, leading instead to further arms race. The same difficulty may be there in our attempts for normalisation of relations with China, though it can be argued that now we can talk from a position of strength.

It is evident that the country's leadership has decided to keep its options regarding nuclear capability open, even while concentrating on using the new power for peaceful purposes only. To that extent a political decision has been made and let us be honest about it.

GLOSSARY

Alpha particle – A positively charged particle emitted by certain radioactive materials. It is made up of two neutrons and two protons bound together, and is identical to the nucleus of a helium atom.

Atom – A particle of matter indivisible by chemical means – the fundamental building block of the chemical elements.

Atomic bomb – A bomb whose energy comes from the fission of heavy elements, such as uranium or plutonium.

Atomic number – The number of protons in the nucleus of an atom – also its positive charge.

Boiling-water reactor – A reactor in which water, used as both coolant and moderator, is allowed to boil in the core. The resulting steam can be used directly to drive a turbine.

Breeder reactor – A reactor that produces more fissile (fissionable) fuel than it consumes. The new fissile material is created by capture in fertile materials of neutrons from fission, a process known as breeding.

Burner reactor – A reactor that produces some fissile material, but less than it consumes.

Chain reaction – A reaction that stimulates its own repetition. In a fission chain reaction a fissionable nucleus absorbs a neutron and fissions, releasing additional neutrons. These in turn can be absorbed by other fissionable nuclei, releasing still more neutrons. A fission chain reaction is self-sustaining when the number of neutrons released in a given time equals or exceeds the number of neutrons lost by absorption in non-fissioning material or by escape from the system.

Containment – The provision of a gas-tight shell or other enclosure around a reactor to confine fission products that otherwise might be released to the atmosphere in the event of an accident.

Control rod – A rod, plate, or tube containing a material that readily absorbs neutrons, used to control the power of a nuclear reactor. By absorbing neutrons, a control rod prevents the neutrons from causing further fission.

Conversion ratio – The ratio of the number of atoms of new fissile material produced in a burner reactor to the original number of atoms of fissile fuel consumed.

Coolant – A substance circulated through a nuclear reactor to remove or transfer heat. Common coolants are water, air, carbon dioxide and liquid sodium.

Core – The central portion of a nuclear reactor containing the fuel elements and usually the moderator, but not the reflector.

Critical mass – The smallest mass of fissile material that will support a self-sustaining chain reaction under stated conditions.

Criticality – The state of a nuclear reactor when it is sustaining a chain reaction.

Curie – The basic unit to describe the intensity of radioactivity in a sample of material. The curie is equal to 37 billion disintegrations per second, which is approximately the rate of decay of one gram of radium.

Decay, radioactive – The gradual decrease in radioactivity of a radioactive substance due to nuclear disintegration. What remains is a different element. Also called radioactive disintegration.

Depleted uranium – Uranium having a smaller percentage of ^{235}U than the 0.7 per cent found in natural uranium. It is obtained from the spent (used) fuel elements.

Doubling time – The time required for a breeder reactor to produce as much fissile material as the amount usually contained in its core plus the amount in its fuel cycle (fabrication, reprocessing, and so on). It is estimated as 10-20 years in typical reactors.

Electron – An elementary particle with a unit negative electrical charge and a mass 1/1837 that of the proton.

Element – One of the 102 known chemical substances that cannot be divided into simpler substances by chemical means. A substance whose atoms all have the same atomic number.

Enriched material – Material in which the percentage of a given isotope present in a material has been artificially increased, so that it is higher than the percentage of that isotope naturally found in the material. Enriched uranium contains more of the fissionable isotope ^{235}U than the naturally occuring percentage (0.7 per cent).

Enrichment – A process by which the relative abundances of the isotopes of a given element are altered, thus producing a form of the element which has been enriched in one particular isotope.

Fallout – Airborne particles and other matter containing radioactive material which fall to the ground following a nuclear explosion.

Fast breeder reactor – A reactor that operates with fast neutrons and produces more fissile material than it consumes.

Fast reactor – A reactor in which the fission chain reaction is sustained primarily by fast neutrons rather than by slow (thermal) or intermediate neutrons. Fast reactors contain little or no moderator to slow down the neutrons from the speeds at which they are ejected from fissioning nuclei.

Fertile material – A material, not itself fissionable by thermal neutrons, which can be converted into a fissile material by irradiation in a reactor. There are two basic fertile materials, ^{238}U and ^{232}Th. When these fertile materials capture neutrons, they are partially converted into fissile ^{239}Pu and ^{233}U respectively.

Fissile material – While sometimes used as a synonym for fissionable material, this term has also acquired a more restricted meaning, namely, any material fissionable by neutrons of all energies, including (and especially) thermal (slow) neutrons as well as fast neutrons: for example ^{235}U and ^{239}Pu.

Fission – The splitting of a heavy nucleus into two approximately equal parts (which are nuclei of lighter elements), accompanied by the release of a relatively large amount of energy and generally one or more neutrons. Fission can occur sponta-

neously, but usually is caused by nuclear absorption of neutrons or other particles.

Fission products – The nuclei (fission fragment) formed by the fission of heavy elements plus the nuclides formed by the fission fragments' radioactive decay.

Fuel – Fissile material used or usable to produce energy in a reactor. Also applied to a mixture, such as natural uranium, in which only part of the atoms are readily fissionable, if the mixture can be made to sustain a chain reaction.

Fuel cycle – The series of steps involved in supplying fuel for nuclear-power reactors. It includes mining, refining, the original fabrication of fuel elements, their use in a reactor, chemical processing to recover the fissionable material remaining in the spent fuel, reenrichment of the fuel material, and refabrication into new fuel elements.

Fuel element – A rod, tube, plate, or other mechanical shape or form into which nuclear fuel is fabricated for use in a reactor.

Fuel inventory – The amount of fissile material in the core of a reactor.

Fuel reprocessing – The processing of reactor fuel to recover the unused fissile material.

Fusion – The formation of a heavier nucleus from two lighter ones (such as hydrogen isotopes), with the attendant release of energy (as in a hydrogen bomb).

GWe – One thousand megawatts of electricity (1,000 MWe).

Gas-cooled reactor – A nuclear reactor in which a gas is the coolant. In such a reactor graphite is often used as the moderator.

Gaseous diffusion – A method of isotopic separation based on the fact that gas atoms or molecules with different masses will diffuse through a porous barrier (or membrane) at different rates. The method is used to separate ^{235}U from ^{238}U; it requires large gaseous diffusion plants and enormous amounts of electric power.

Graphite – A very pure form of carbon used as a moderator in some nuclear reactors.

Half-life – The time in which half the atoms of a particular radioactive substance disintegrate to another nuclear form. Measured half-lives vary from millionths of a second to billions of years.

Heavy water – Water containing significantly more than the natural proportion (one in 6500) of heavy hydrogen (deuterium) atoms to ordinary hydrogen atoms. Heavy water is used as a moderator in some reactors because it slows down neutrons effectively and also has a low cross-section (probability) for absorption of neutrons.

Heavy-water moderated reactor – A reactor that uses heavy water as its moderator. Heavy water is an excellent moderator and thus permits the use of inexpensive natural (unenriched) uranium as a fuel.

Hydrogen – The lightest element, number one in the atomic series. It has two natural isotopes of atomic weights one and two. The first is ordinary hydrogen, or light hydrogen; the second is deuterium, or heavy hydrogen. A third isotope, tritium, atomic weight three, is a radioactive form produced in reactors.

Hydrogen bomb – A nuclear weapon that derives its energy largely from fusion (thermonuclear bomb).

Isotope – One of two or more atoms with the same atomic number (the same chemical element) but with different atomic weights.

Light water – Ordinary water (H_2O), as distinguished from heavy water (D_2O).

Light-water reactor – A reactor that uses ordinary water as moderator or coolant. There are two types – boiling-water reactor and pressurized-water reactors.

MWe – One million watts of electricity.

Megaton energy – The energy of a nuclear explosion which is equivalent to that of an explosion of one million tons (or 1,000 kilotons) of TNT.

Megawatt-day per ton – A unit used for expressing the burn-up of fuel in a reactor: specifically, the number of megawatt-days of heat output per metric ton of fuel in the reactor.

Moderator – A material, such as ordinary water, heavy water, or graphite used in a reactor to slow down fast neutrons to increase the probability of further fission.

Molecule – A group of atoms held together by chemical forces.

Natural uranium – Uranium as found in nature, containing 0.7% of ^{235}U, 99.3% of ^{238}U, and a trace of ^{234}U.

Neutron – An uncharged elementary particle with a mass slightly greater than that of the proton, and found in the nucleus of every atom heavier than hydrogen.

Neutron capture – The process in which an atomic nucleus absorbs or captures a neutron.

Nuclear device – A nuclear explosive used for peaceful purposes, tests or experiments. The term is used to distinguish these explosives from nuclear weapons, which are packaged units ready for transportation or use by military forces.

Nuclear energy – The energy liberated by a nuclear reaction (fission or fusion) or by radioactive decay.

Nuclear explosive – An explosive based on fission or fusion of atomic nuclei.

Nuclear-power plant – Any device or assembly that converts nuclear energy into useful power. In a nuclear electric power plant, heat produced by a reactor is used to produce steam to drive a turbine that in turn drives an electricity generator.

Nuclear reactor – A device in which a fission chain reaction can be initiated, maintained, and controlled. Its essential component is a core with fissionable fuel. It usually has a moderator, a reflector, shielding, coolant, and control mechanisms.

Nuclear weapons – A collective term for atomic bombs and hydrogen bombs. Any weapon based on a nuclear explosive.

Nucleus – The small positively charged core of an atom. It is only about 1/10 000 the diameter of the atom but contains nearly all the atom's mass. All nuclei contain both protons and neutrons, except the nucleus of ordinary hydrogen, which consists of a single proton.

Nuclide – Species of atom characterized by the number of protons and the number of neutrons in its nucleus.

Plutonium – A heavy, radioactive, man-made, metallic element with atomic number 94. Its most important isotope is fissionable ^{239}Pu, produced by neutron irradiation of ^{238}U. It is used for reactor fuel and in weapons.

Power reactor – A reactor designed to produce useful nuclear power, as distinguished from reactors used primarily for research or for producing radiation or fissionable materials.

Pressure vessel – A strong-walled container housing the core of most types of power reactors: it usually also contains a moderator, reflector, thermal shield, and control rods.

Pressurized-water reactor – A power reactor in which heat is transferred from the core to a heat exchanger by water kept under high pressure to achieve high temperature without boiling in the primary system. Steam is generated in a secondary circuit.

Production reactor – A reactor designed primarily for large-scale production of ^{239}Pu by neutron irradiation of ^{238}U. Also a reactor used primarily for the production of radioactive isotopes.

Proton – An elementary particle with a single positive electrical charge and a mass approximately 1 837 times that of the electron. The nucleus of an ordinary or light hydrogen atom. Protons are constituents of all nuclei. The atomic number of an atom is equal to the number of protons in its nucleus.

Radioactive contamination – Deposition of radioactive material in any place.

Radioactive waste – Equipment and materials (from nuclear operations) which are radioactive and for which there is no further use.

Radioactivity – The spontaneous decay or disintegration of an unstable atomic nucleus.

Reactor cooling pond – A mass of water in which reactor fuel elements are placed, immediately after being taken out of the reactor core, to allow the radioactive fission products to decay. The elements are eventually transported from the pond to a reprocessing plant.

Reflector – A layer of material immediately surrounding a reactor core which scatters back or reflects into the core many neutrons that would otherwise escape. The returned neutrons can then cause more fissions and improve the neutron economy of the reactor. Common reflector materials are graphite, beryllium and natural uranium.

Research reactor – A reactor primarily designed to supply neutrons or other ionizing radiation for experimental purposes. It may also be used for training, materials testing and production of radionuclides.

Safety rod – A standby control rod used to shut down a nuclear reactor rapidly in emergencies.

Spent fuel element – Nuclear reactor fuel element that has been irradiated to an extent that it can no longer effectively sustain a chain reaction.

Spontaneous fission – Fission that occurs without an external stimulus.

Thermal-to-electric conversion efficiency – The ratio of the electric power produced by a power plant to the amount of heat produced by the fuel; a measure of the efficiency with which the plant converts thermal to electrical energy.

Thermal (slow) neutron – A neutron in thermal equilibrium with its surrounding medium. Thermal neutrons are those that have been slowed down by a moderator to an average speed of about 2 200 metres per second (at room temperature) from the much higher initial speeds they had when expelled by fission.

Thermonuclear reaction – A reaction in which very high temperatures bring about the fusion of two light nuclei to form the nucleus of a heavier atom, releasing a large amount of energy. In a hydrogen bomb, the high temperature to initiate the thermonuclear reaction is produced by a preliminary fission reaction.

Thorium – A naturally radioactive element with atomic number 90 and, as found in nature, an atomic weight of approximately 232. The fertile ^{232}Th isotope is abundant and can be transmuted to fissionable ^{233}U by neutron irradiation.

TNT equivalent – A measure of the energy released in the detonation of a nuclear explosive expressed in terms of the weight of TNT (the chemical explosive, trinitrotoluene) which would release the same amount of energy when exploded. It is usually expressed in kilotons or megatons.

Transuranic element (isotope) – An element beyond uranium in the Periodic Table, that is, with an atomic number greater than 92.

Uranium – A radioactive element with the atomic number 92 and, as found in natural ores, an average atomic weight of approximately 238. The two principal natural isotopes are ^{235}U (0.7% of natural uranium), which is fissile, and ^{238}U (99.3% of natural uranium) which is fertile. Natural uranium also includes a minute amount of ^{234}U.

Weapons-grade plutonium (uranium) – Plutonium containing at least 90 per cent of ^{239}Pu and no more than 10 per cent of other plutonium isotopes. Uranium enriched to at least 95% ^{235}U.

Yellow cake – Uranium U_3O_8.

Yield – The total energy released in a nuclear explosion. It is usually expressed in equivalent tons of TNT (the quantity of TNT required to produce a corresponding amount of energy).

Source: Based on *Nuclear Terms, A Brief Glossary,* (US-Atomic Energy Commission, Division of Technical Extension, Oak Ridge, Tennessee, 1967).